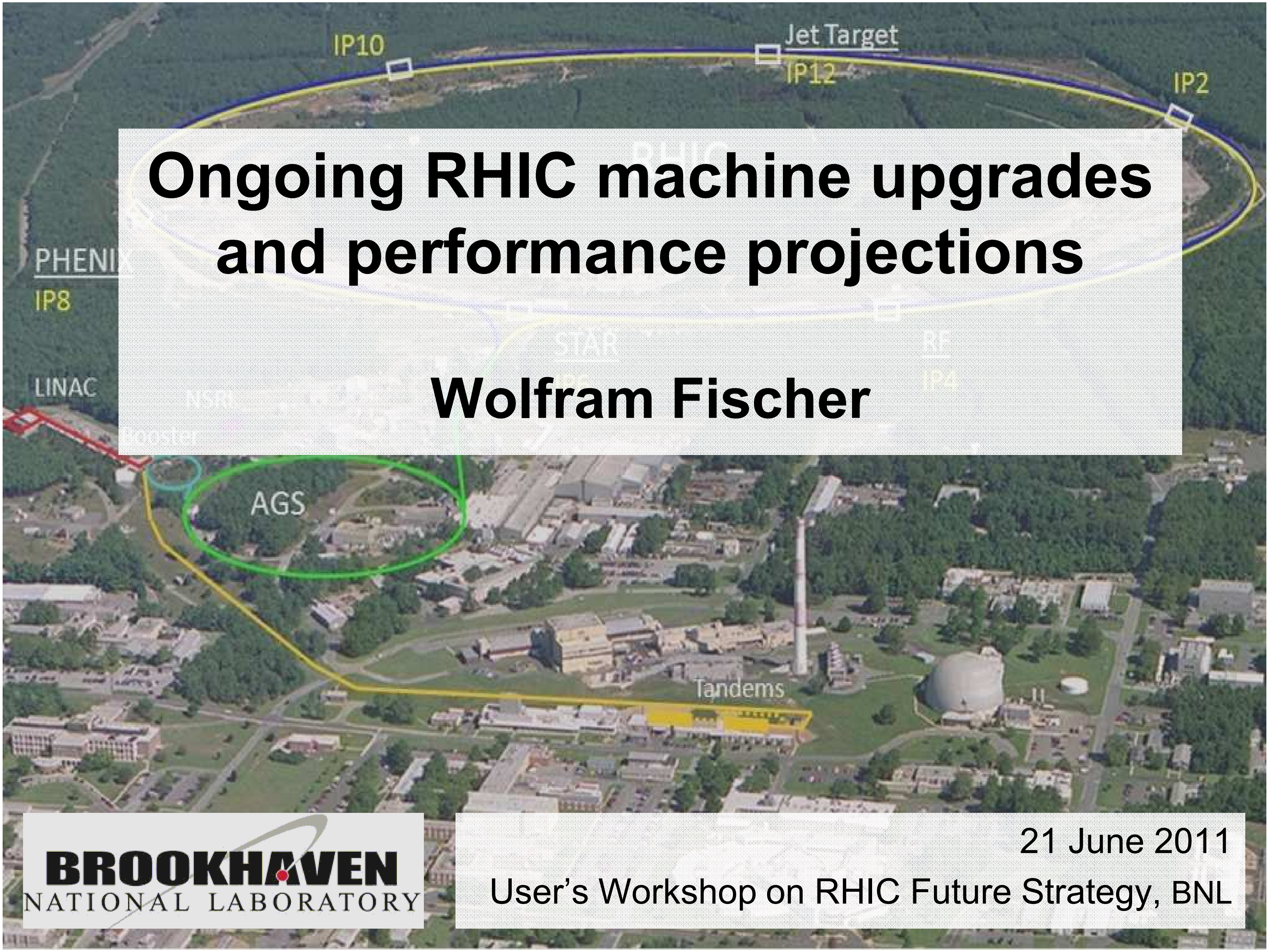


Ongoing RHIC machine upgrades and performance projections

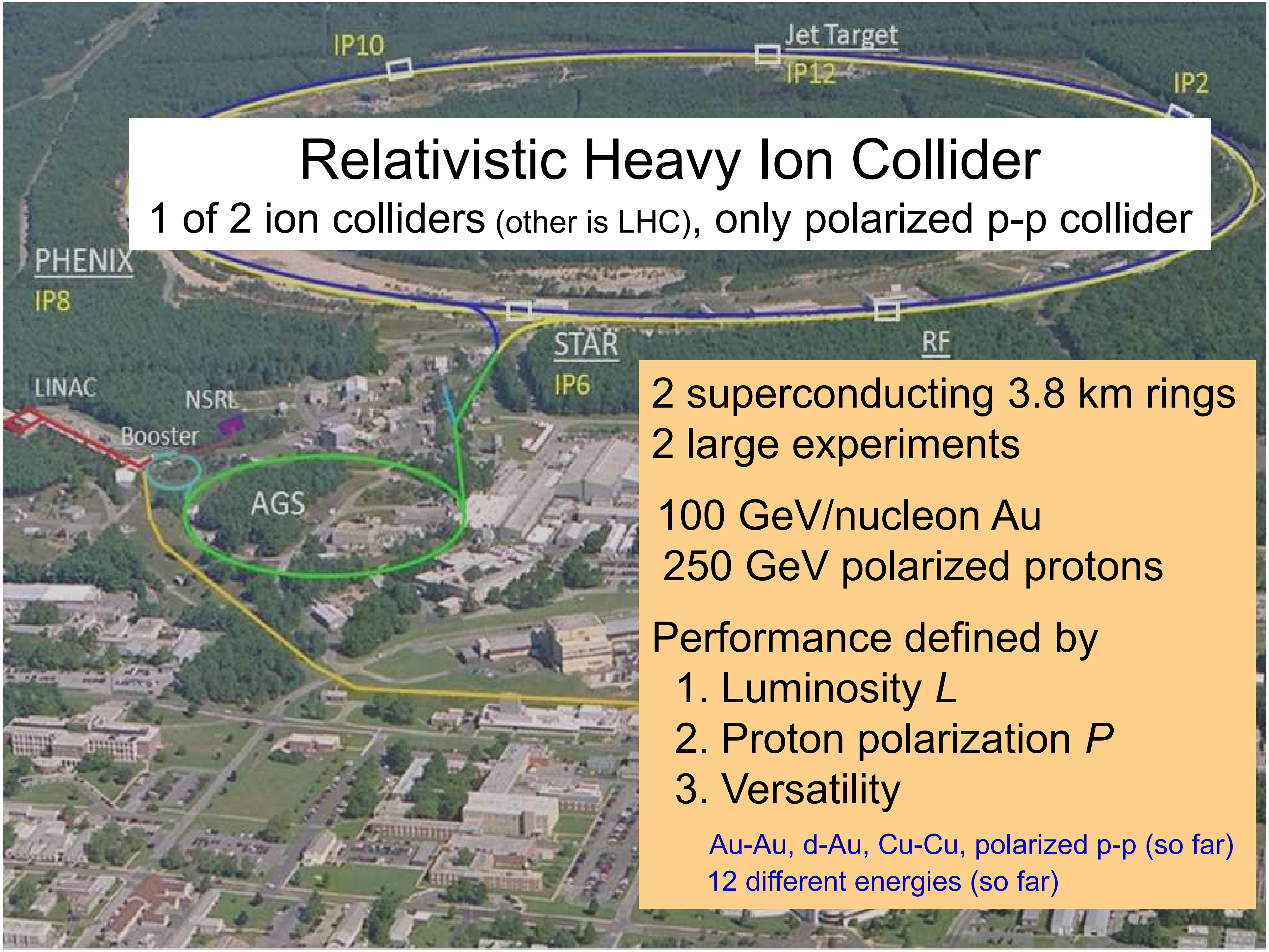
Wolfram Fischer

BROOKHAVEN NATIONAL LABORATORY

21 June 2011
User's Workshop on RHIC Future Strategy, BNL

Relativistic Heavy Ion Collider

1 of 2 ion colliders (other is LHC), only polarized p-p collider



2 superconducting 3.8 km rings
2 large experiments

100 GeV/nucleon Au
250 GeV polarized protons

Performance defined by

1. Luminosity *L*
2. Proton polarization *P*
3. Versatility

Au-Au, d-Au, Cu-Cu, polarized p-p (so far)
12 different energies (so far)

Content

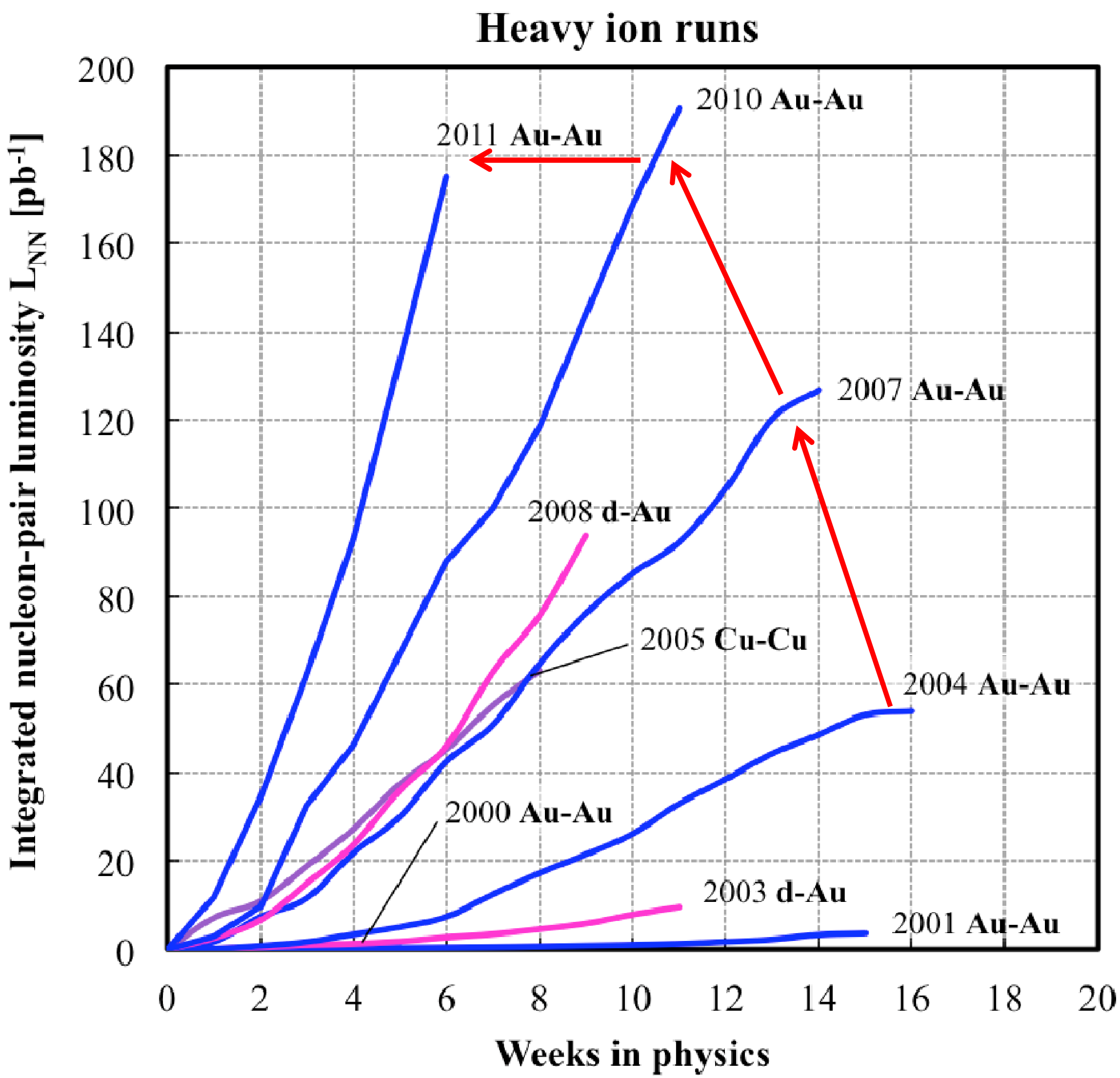
Heavy ion status and upgrades

- Stochastic cooling
- 56 MHz SRF
- Electron Beam Ion Source (EBIS)

Polarized proton status and upgrades

- A_nDY as 3rd colliding beam experiment
- Polarized source
- Electron lenses
- Energy increase, polarized ^{3}He

RHIC heavy ions – luminosity evolution to date



<L> = 15x design in 2011

About 2x increase in L_{int}/week each

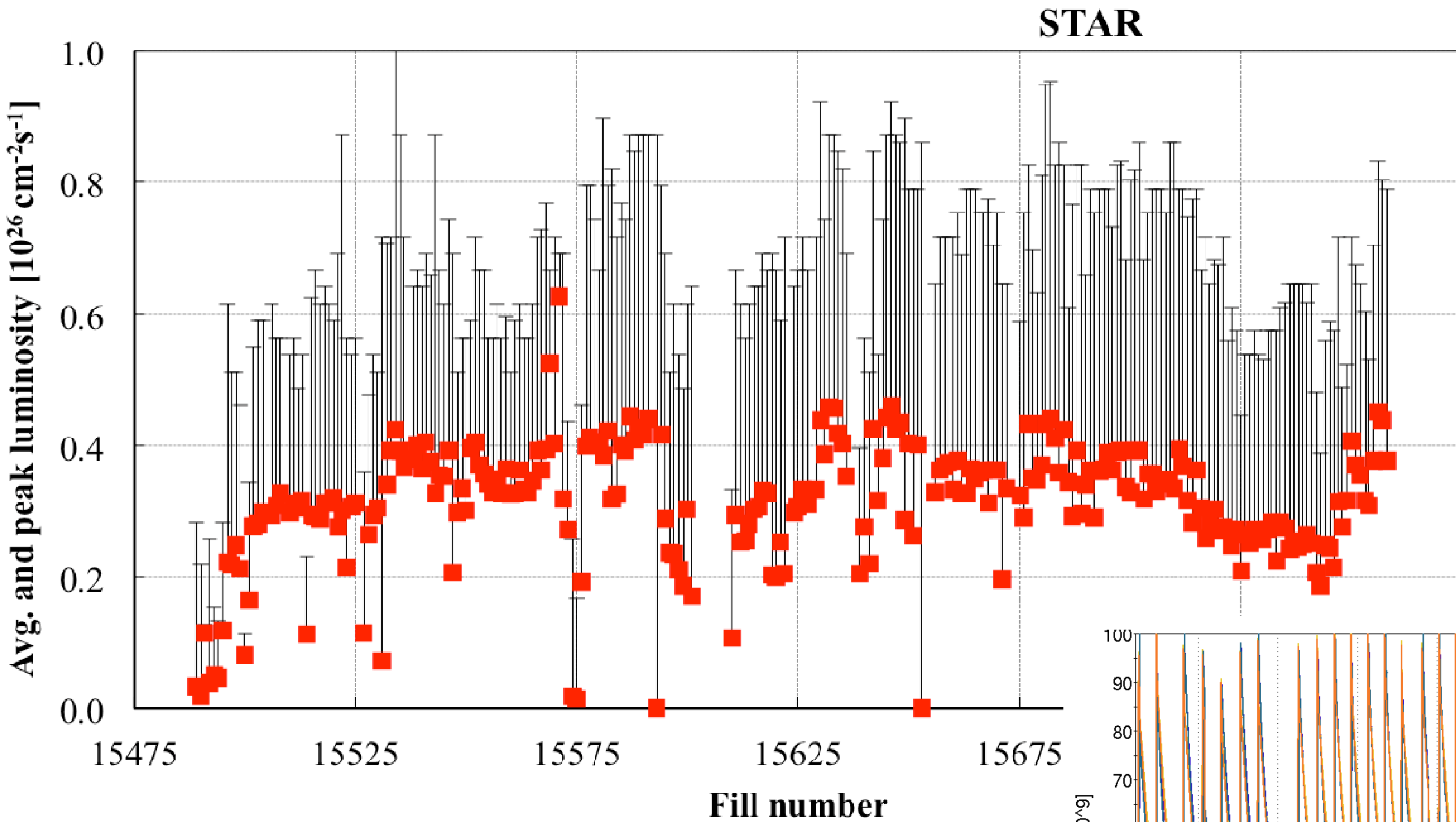
- Run-4 to Run-7
- Run-7 to Run10
- Run-10 to Run-11

Rate of progress will slow down – burn off 50% of beam in collisions already

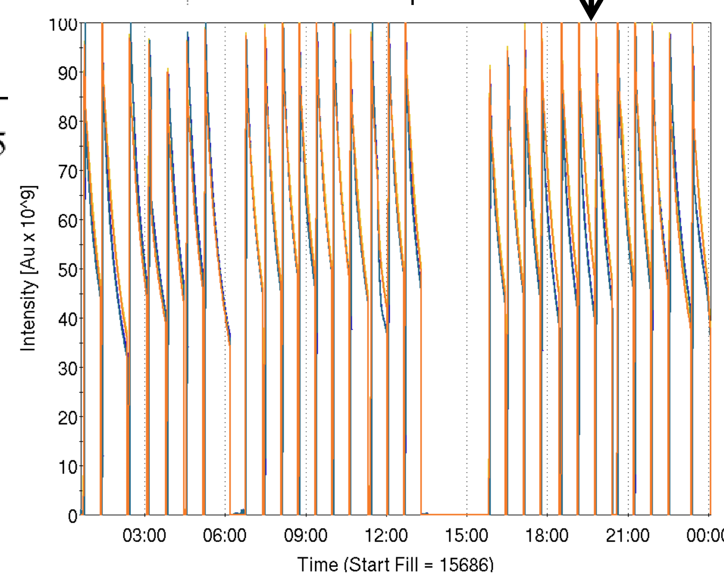
$L_{NN} = L\, N_1 N_2$ (= luminosity for beam of nucleons, not ions)

Run-11 Au-Au $\sqrt{s_{NN}}$ = 19.6 GeV (nominal injection energy)

Run Coordinator: Greg Marr



Typical day (04/25/11)

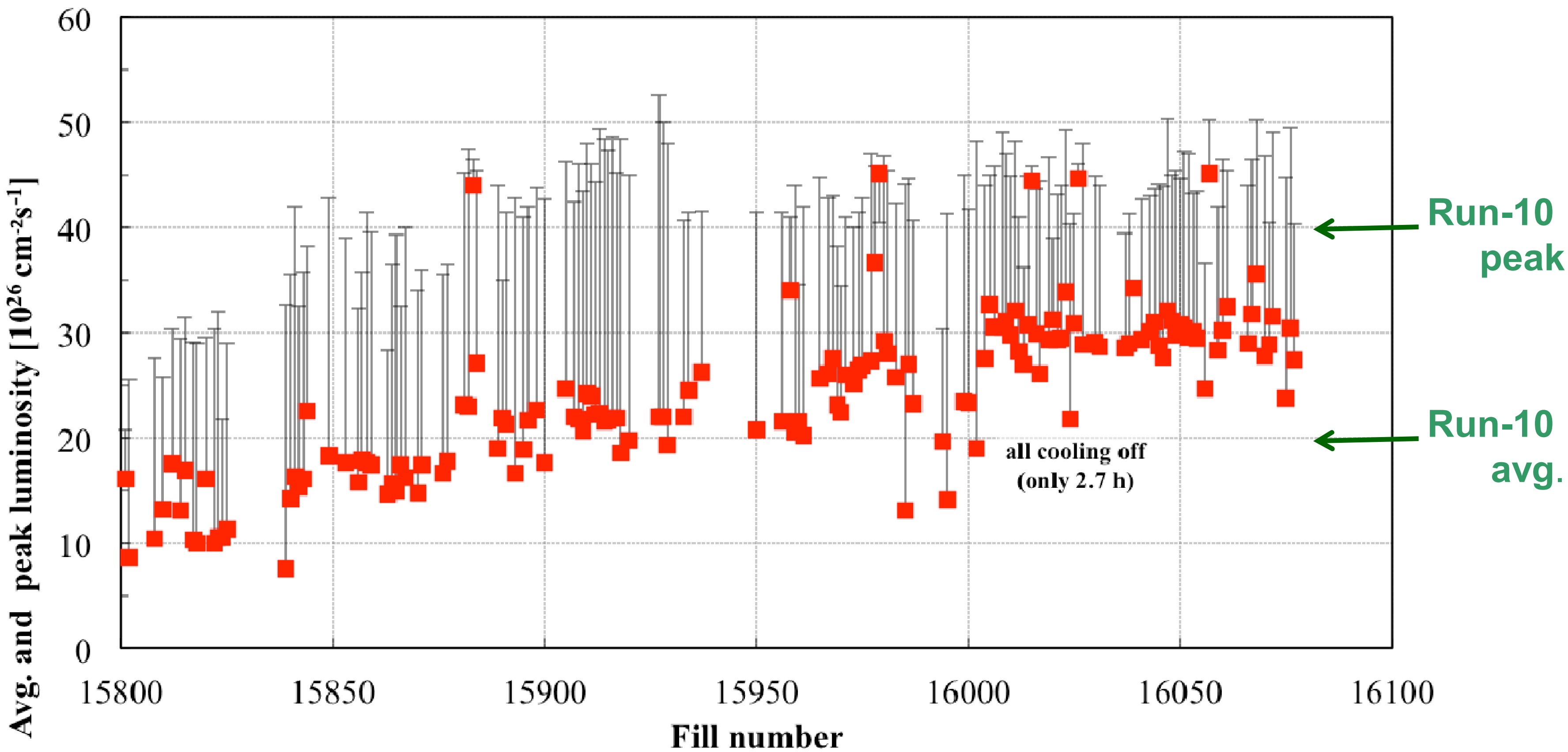


3 days to physics, 10 days in physics
35 min store length
71% of calendar time in store

STAR : 17.5 μb^{-1} (175x Run-2)
PHENIX: 15.7 μb^{-1} (157x Run-2)

Run-11 Au-Au $\sqrt{s_{NN}}$ = 200 GeV (finished yesterday)

Run Coordinator: Greg Marr

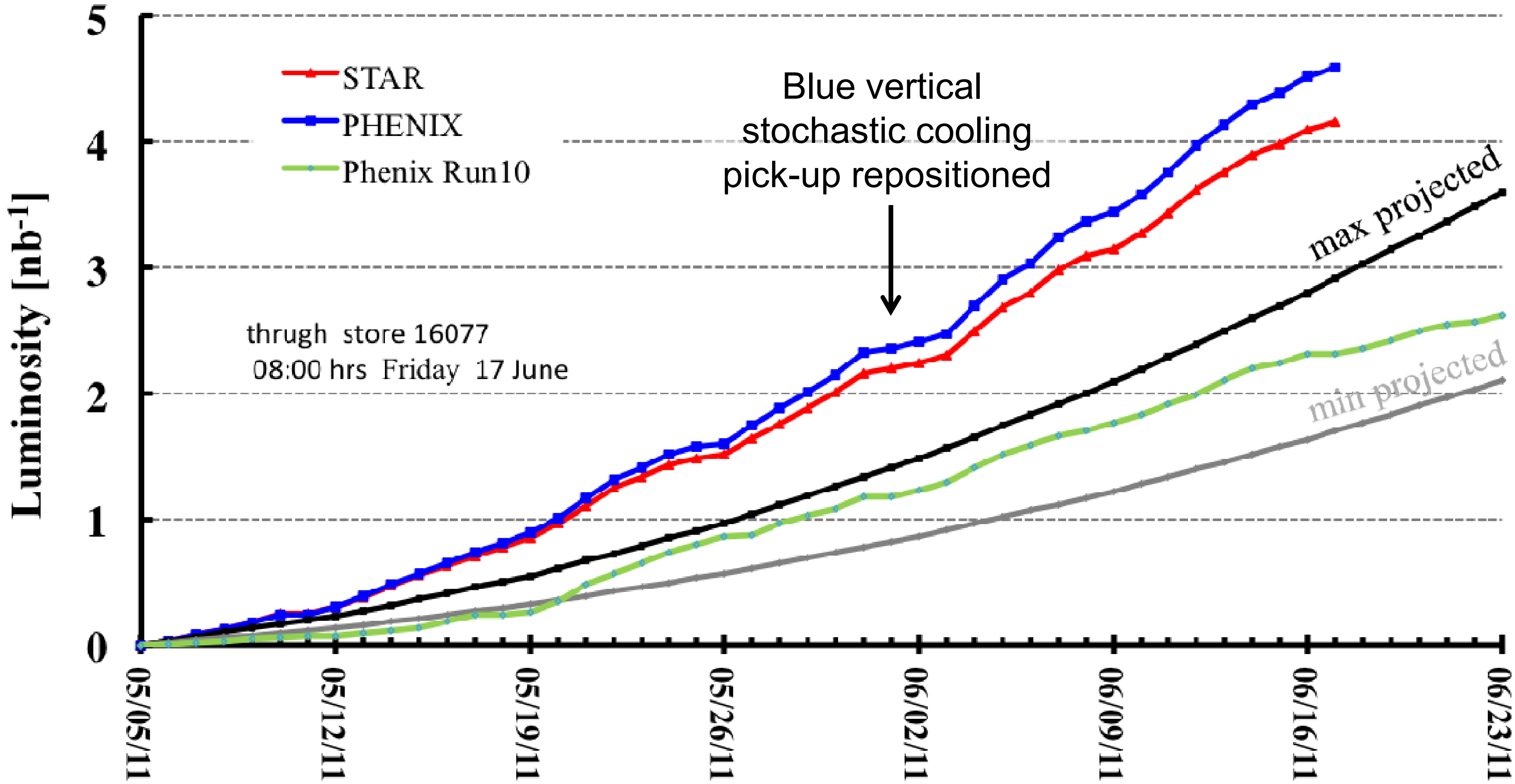


Setup to physics in 4 days (from operation at injection energy)

Exceeded peak, average, and weekly luminosities from Run-10.

Run-11 Au-Au $\sqrt{s_{NN}}$ = 200 GeV (finished yesterday)

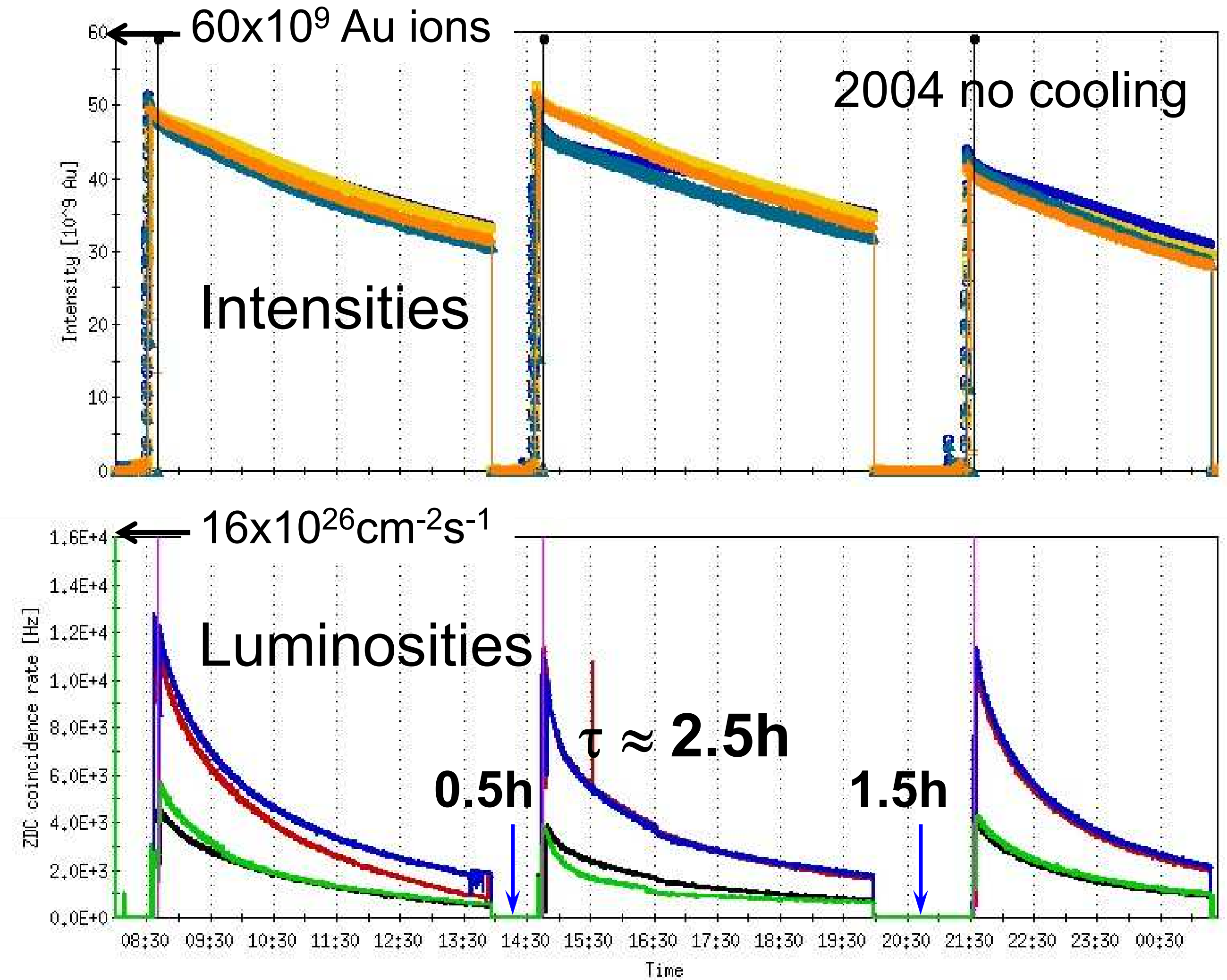
Run Coordinator: Greg Marr



Working on $\sqrt{s_{NN}}$ = 27 GeV now …

RHIC heavy ions – luminosity limit IBS

Intrabeam scattering leads to debunching and transverse emittance growth



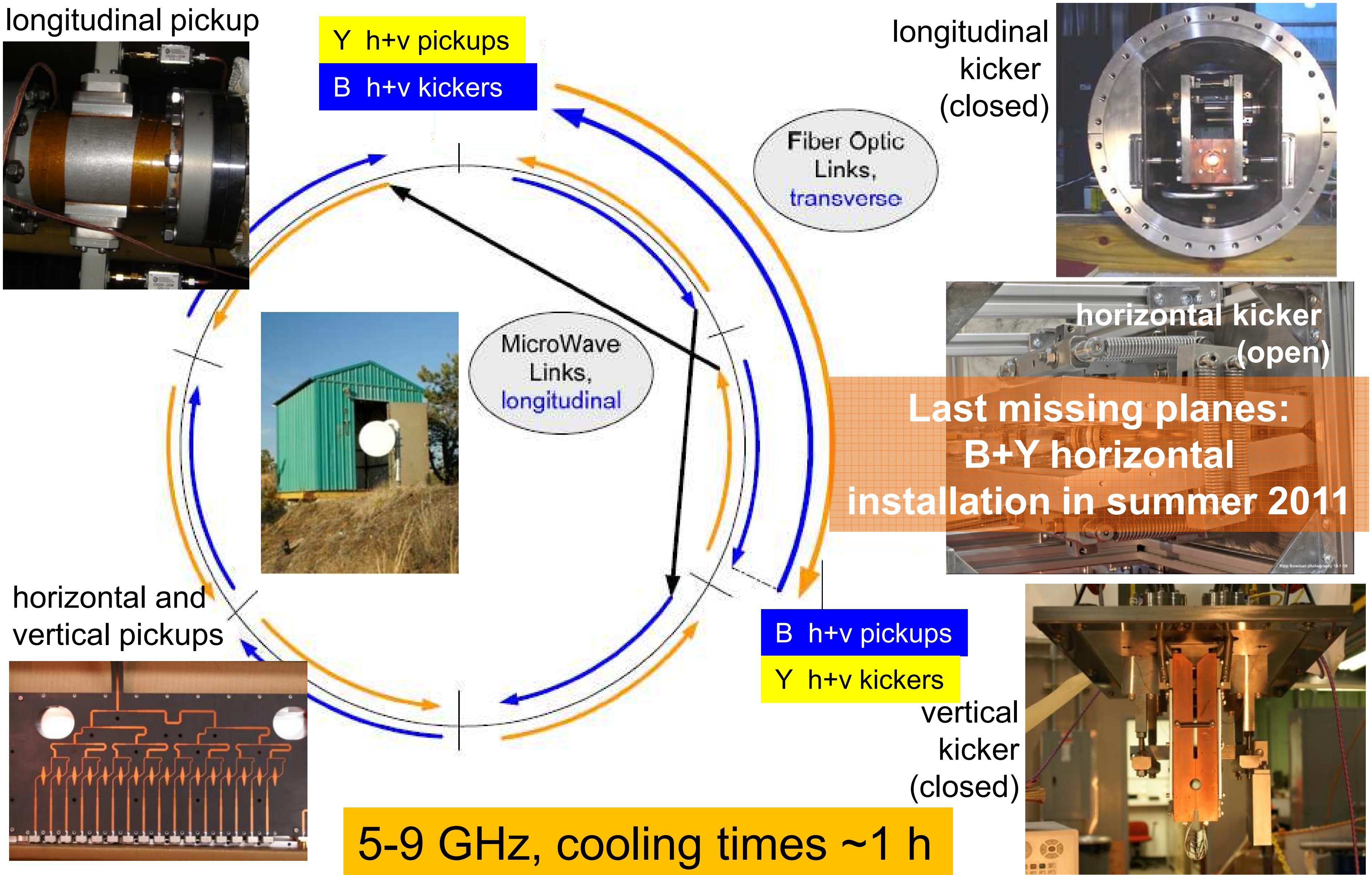
growth rates

$$\tau^{-1} \propto \frac{Z^4}{A^2}\frac{N_b}{\gamma}$$

[Factor 15 between Au an p]

- Maximize focusing in all dimensions
- Frequent refills
- Cooling at full energy

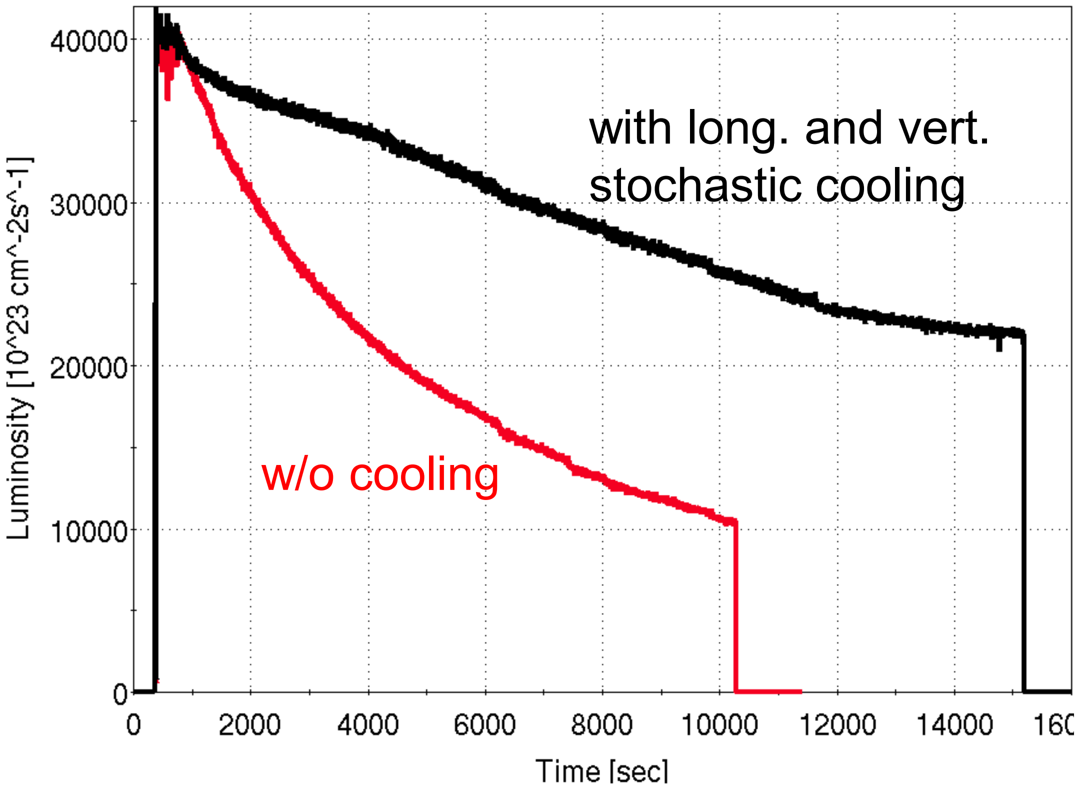
RHIC – 3D stochastic cooling for heavy ions



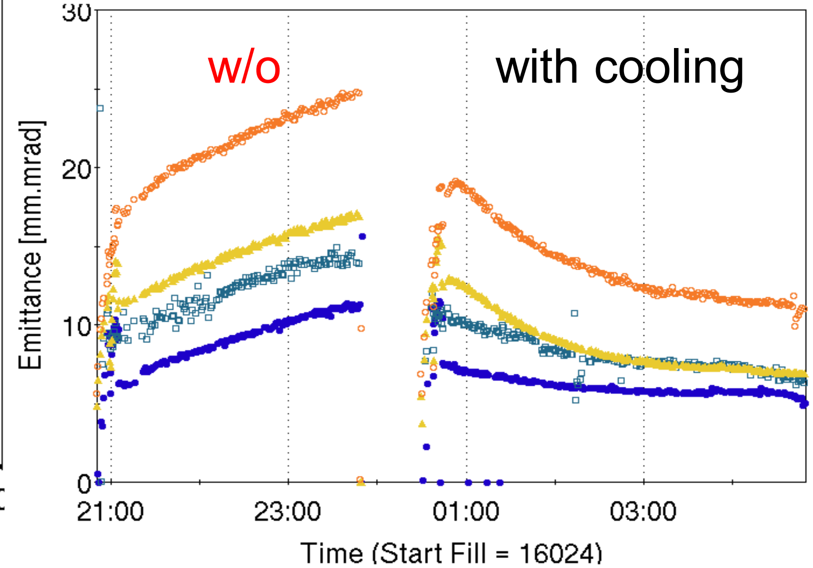
M. Brennan, M. Blaskiewicz, F. Severino, Phys. Rev. Lett. **100** 174803 (2008); PRST-AB, PAC, EPAC

RHIC – effect of stochastic cooling in Run-11

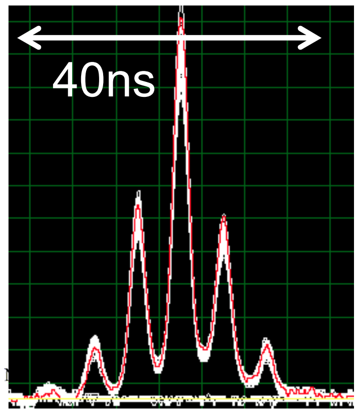
luminosity in 2 consecutive stores



Factor 2 gain in average luminosity from stochastic cooling so far

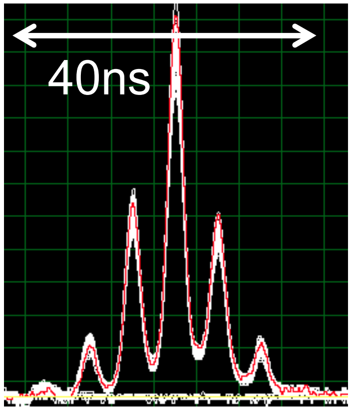


strong transverse cooling makes longitudinal cooling less efficient, i.e. these longitudinal profiles at the end of a store with be more pronounced with horizontal cooling next year



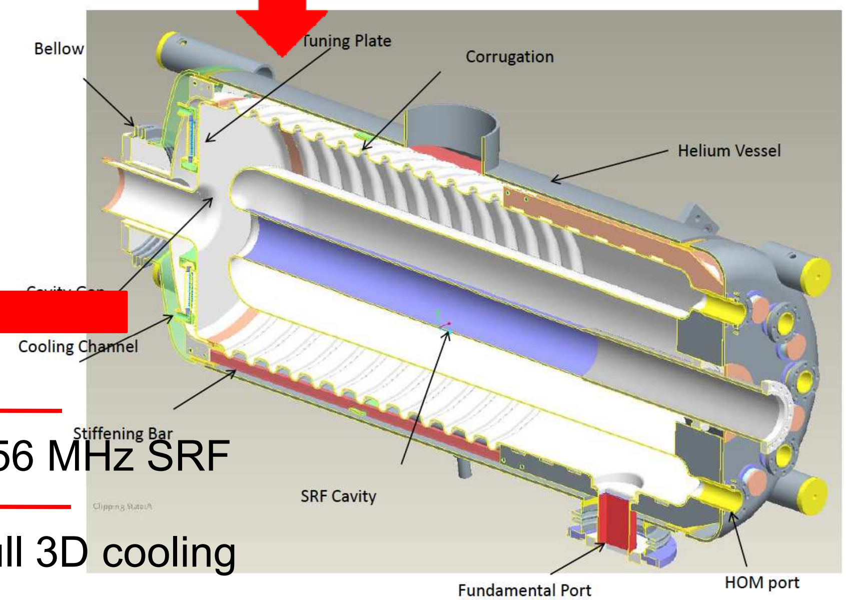
[hourglass factor 0.75 at beginning, 0.55 at end of store]

56 MHz SRF for heavy ions – under construction (I. Ben-Zvi et al.)

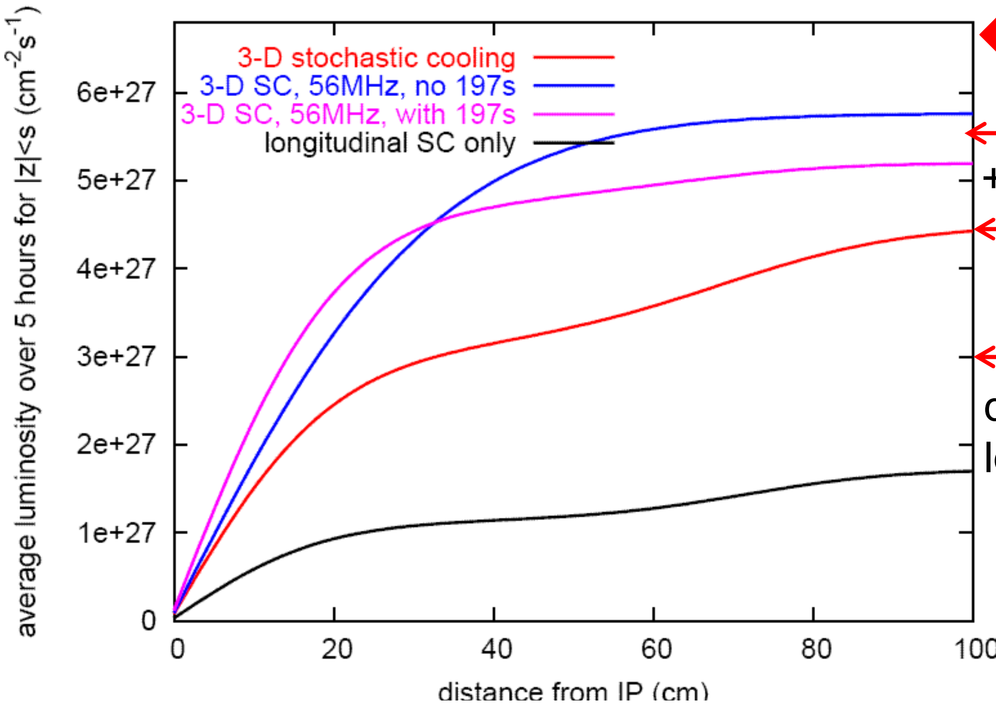


Longitudinal profile at end of store
- even with cooling ions migrate into neighboring buckets
- can be reduced with increased longitudinal focusing

Commissioning planned for Run-14



Average luminosity vs. vertex size



+ 56 MHz SRF

full 3D cooling

demonstrated 2011
long. + ver. cooling

Calculation by M. Blaskiewicz

- $\lambda/4$ Ni resonator
- common to both beams
- beam driven
- 56 MHz, 2 MV

RHIC heavy ions – other luminosity limits

Operate close to a number of other limits:

- Instabilities on ramp at transition (γ_{tr} = 26) ⟵ at limit in Run-7
  driven by machine impedance and electron cloud
- Beam loading during rf rebucketing ⟵ at limit in Run-10
  limit removed last summer by separating common storage cavities
- Intensity limit of beam dump (quench Q4) ⟵ at limit in Run-10
  limit removed last summer by inserting sleeves in beam dump pipe
- Bunch intensity limit from injector chain ⟵ at limit in Run-11
  injected $N_b = 1.5\text{x}10^9$ in Run-11
- Chromatic aberrations with small β^*
  about 50% of particle loss due to burn-off,
  other 50% largely due to off-momentum dynamic aperture
  tested β^* squeeze in store after cooling to equilibrium

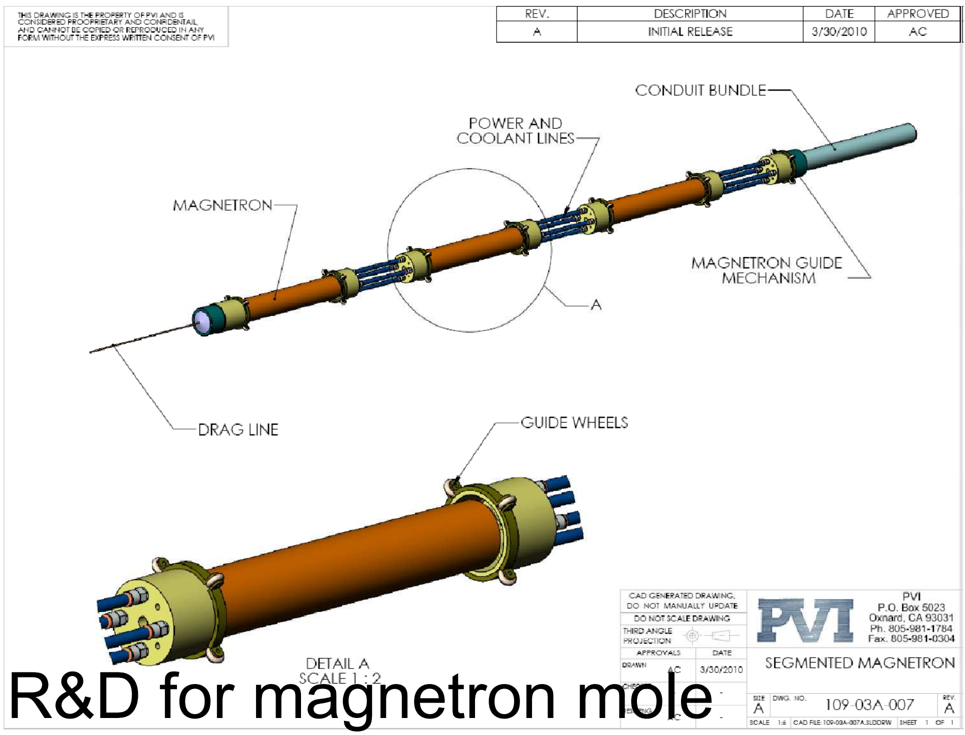
Above list changes from year to year as most limiting effects are mitigated.

Upgrades for heavy ions and polarized protons – in situ-coating

A. Hershkovich et al.

- Electron clouds limit
  - Ion intensity (through instability at transition)
  - Proton emittance at injection, and intensity
- Warm parts are largely coated with NEG
- Cold arcs are stainless steel, not coated

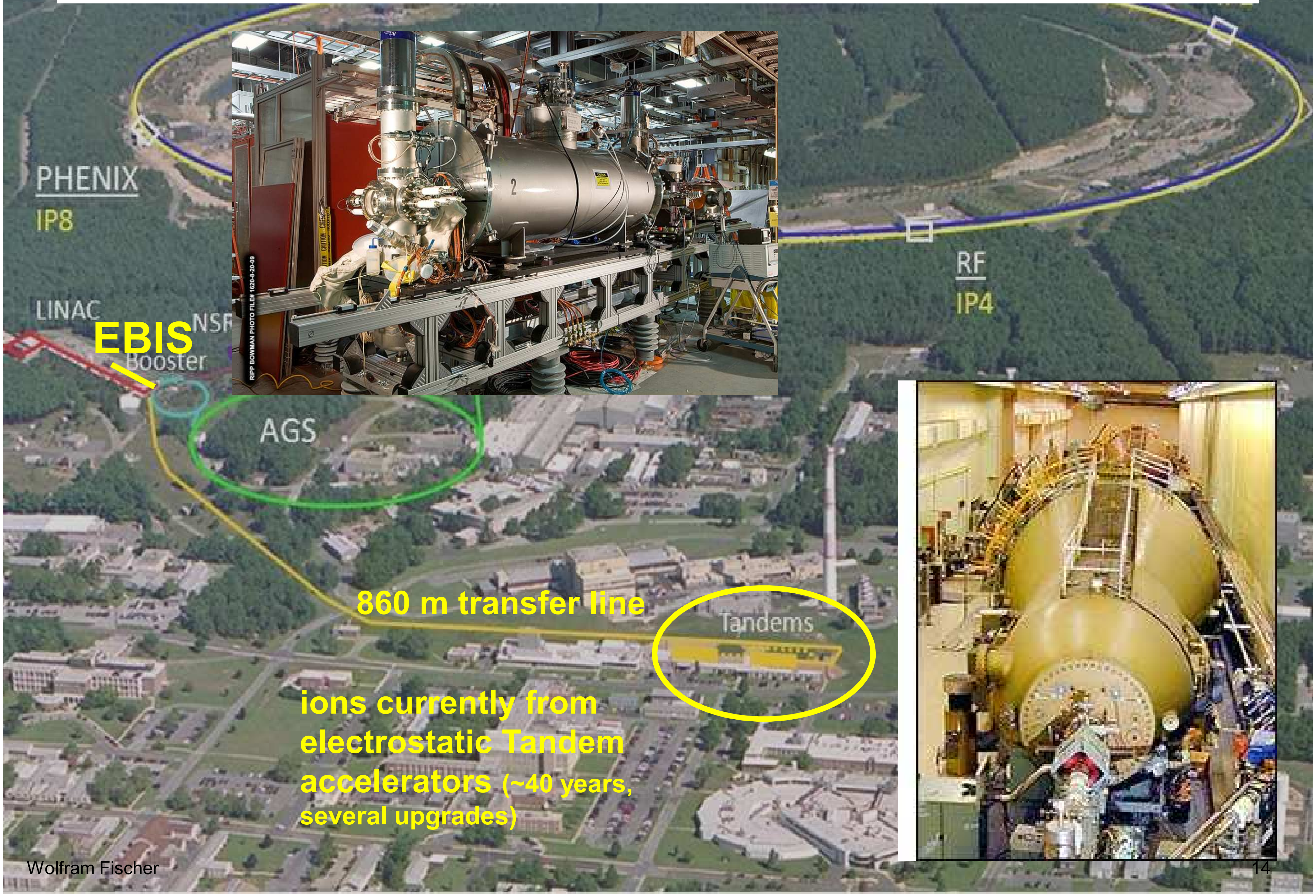
Need in-situ coating for arcs



R&D for magnetron mole

Test tube coated with Cu

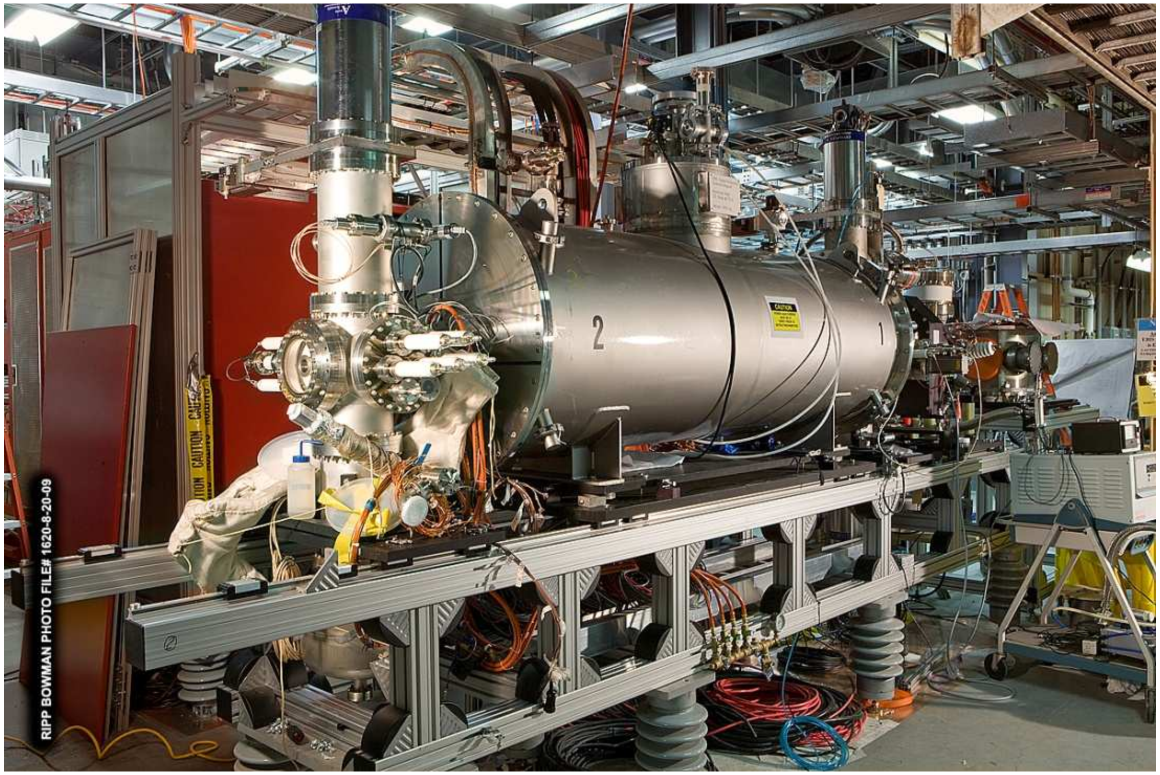
Electron Beam Ion Source (EBIS) (J. Alessi et al.)



ions currently from electrostatic Tandem accelerators (~40 years, several upgrades)

Electron Beam Ion Source (EBIS) (J. Alessi et al.)

- 10 A electron beam creates desired charge state(s) in trap within 5 T superconducting solenoid
- Accelerated through RFQ and linac, injected into AGS Booster
- All ion species incl. noble gas, uranium and polarized ^{3}He



Operated for NSRL with
- He^{+}, He^{2+}, Ne^{5+}, Ne^{8+}, Ar^{11+}, Ti^{18+}, Fe^{20+}

Commissioning for RHIC under way
- Work on 4x Au^{32+} increase to design intensity
  2x from electron current,
  2x from transmission
- Received U cathode
- Tandem still available as backup next year

Asymmetric collisions (p-Au)

- p-Au was considered in RHIC design (D. Trbojevic), no operation yet
  100.8 GeV p on 100.0 GeV/nucleon Au ($\gamma_p = \gamma_{Au} = 107.4$)
- **Need to translate DX magnets horizontally by 4.33 cm**
  p are bent stronger than Au^{79+}
- For energy scan need to match Lorentz factor γ of both beams

Parameter	unit	p-Au		p-Au	
No of bunches	…	111	111	111	111
Ions/bunch, initial	10^9	100	1.0	200	1.2
Average beam current/ring	mA	139	110	278	132
Stored energy per beam	MJ			0.36	0.42
β^*	m	0.85		0.60	
Hour glass factor	…	1.00		0.91	
Beam-beam parameter ξ/IP	10^{-3}	4.3	1.7	5.2	3.5
Peak luminosity	10^{28} cm^{-2}s^{-1}	30		95	
Average / peak luminosity	%	60		60	
Average store luminosity	10^{28} cm^{-2}s^{-1}	18		57	
Time in store	%	55		55	
Maximum luminosity/week	nb^{-1}			189	
Minimum luminosity/week	nb^{-1}	60			

Low energy collider operation

Au-Au energy scan with E = 3.85, 5.75, 9.8, 13.5, 19.5, 31.2, 100 GeV/nucleon

Up to nominal injection energy (9.8 GeV/nucleon) luminosity can be enhanced by electron cooling, use of Fermilab Pelletron possible (other options exist)

Have moved back by 2 year possible start of this upgrade due to manpower demand and needed guidance from experiment (completion ≥Run-17)

Cooling into space charge limit
ΔQ_{sc} ~ 0.05 **(new collider regime)**

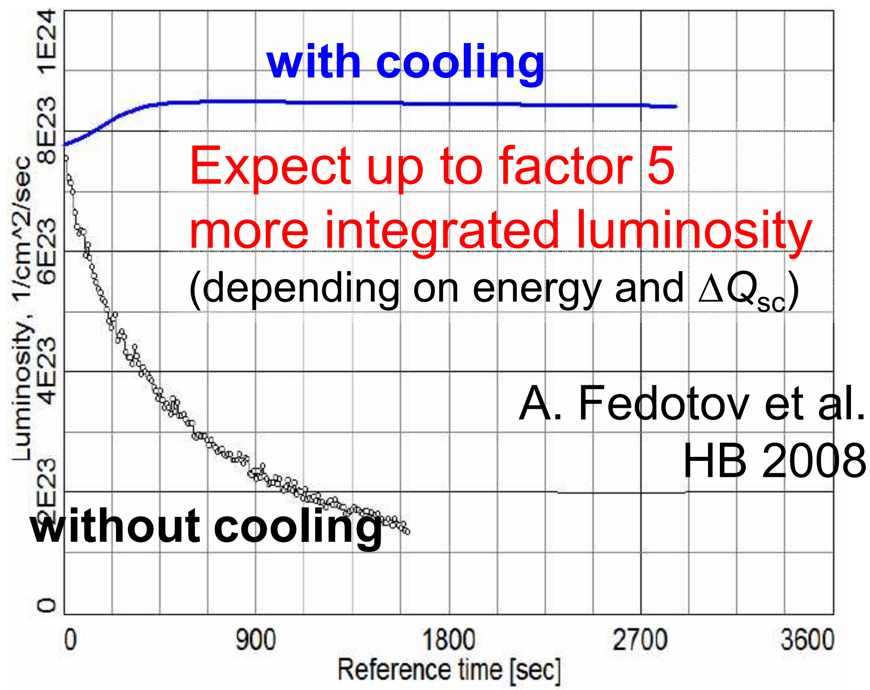
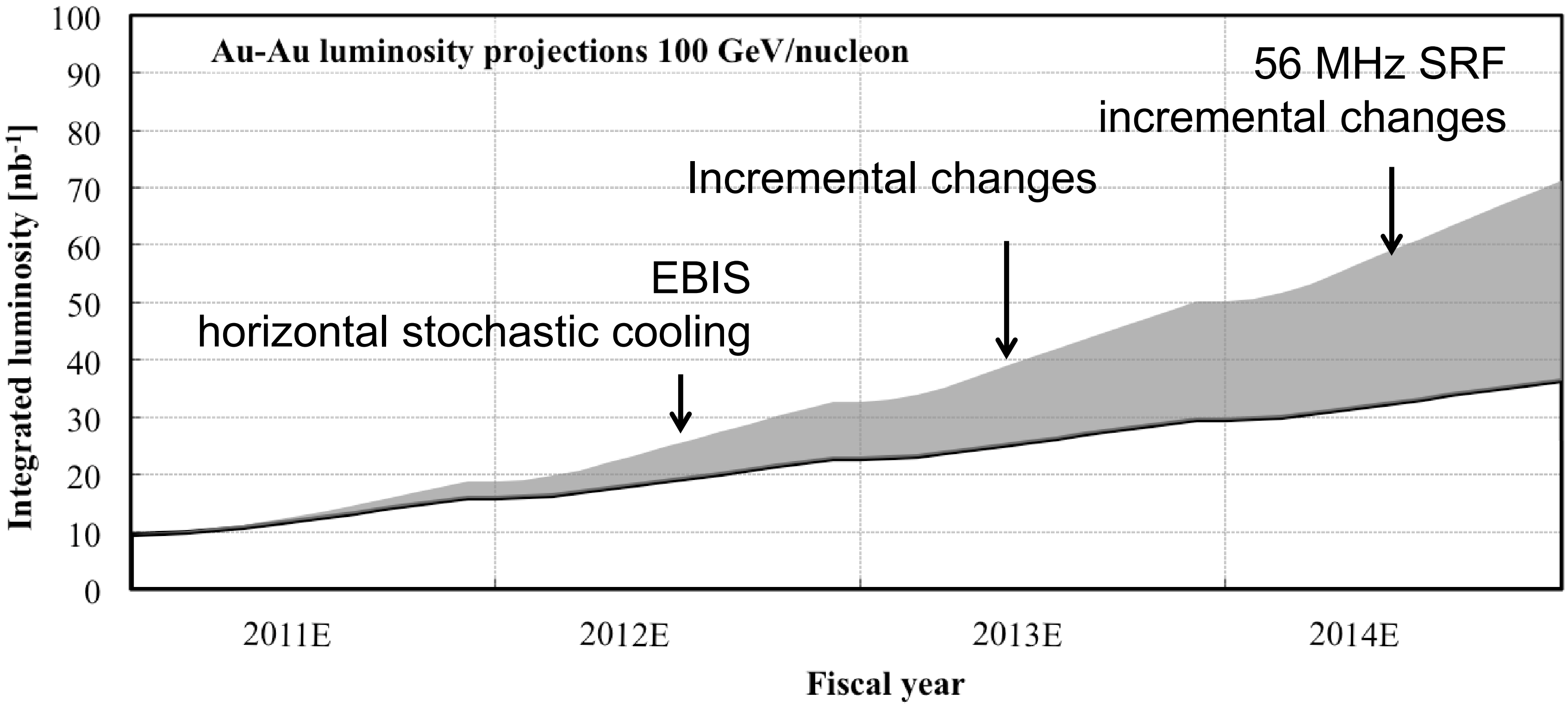


Figure 4. Simulation of luminosity with (blue line) and without (black dots) electron cooling at γ=2.7.

Luminosity and Polarization Goals

Parameter	unit	Achieved	With full stoch. cooling and 56 MHz cavity	
Au-Au operation		**2011**	**≥ 2012**	
Energy	GeV/nucleon	100	100	
No of bunches	…	111	111	
Bunch intensity	10^9	1.3	1.1	
Average Luminosity	**10^{26} cm^{-2} s^{-1}**	**30**	**40**	
p↑- p↑ operation		**2011**	**≥ 2012**	**≥ 2014**
Energy	GeV	100 / 250	100 / 250	250
No of bunches	…	109	109	109
Bunch intensity	10^{11}	1.3 / 1.65	1.3 / 1.7	2.0
Average Luminosity	**10^{30} cm^{-2} s^{-1}**	**24 / 90**	**30 / 150**	**300**
Polarization	**%**	**56 / 46**	**65**	**70**

Projections projection for Au-Au

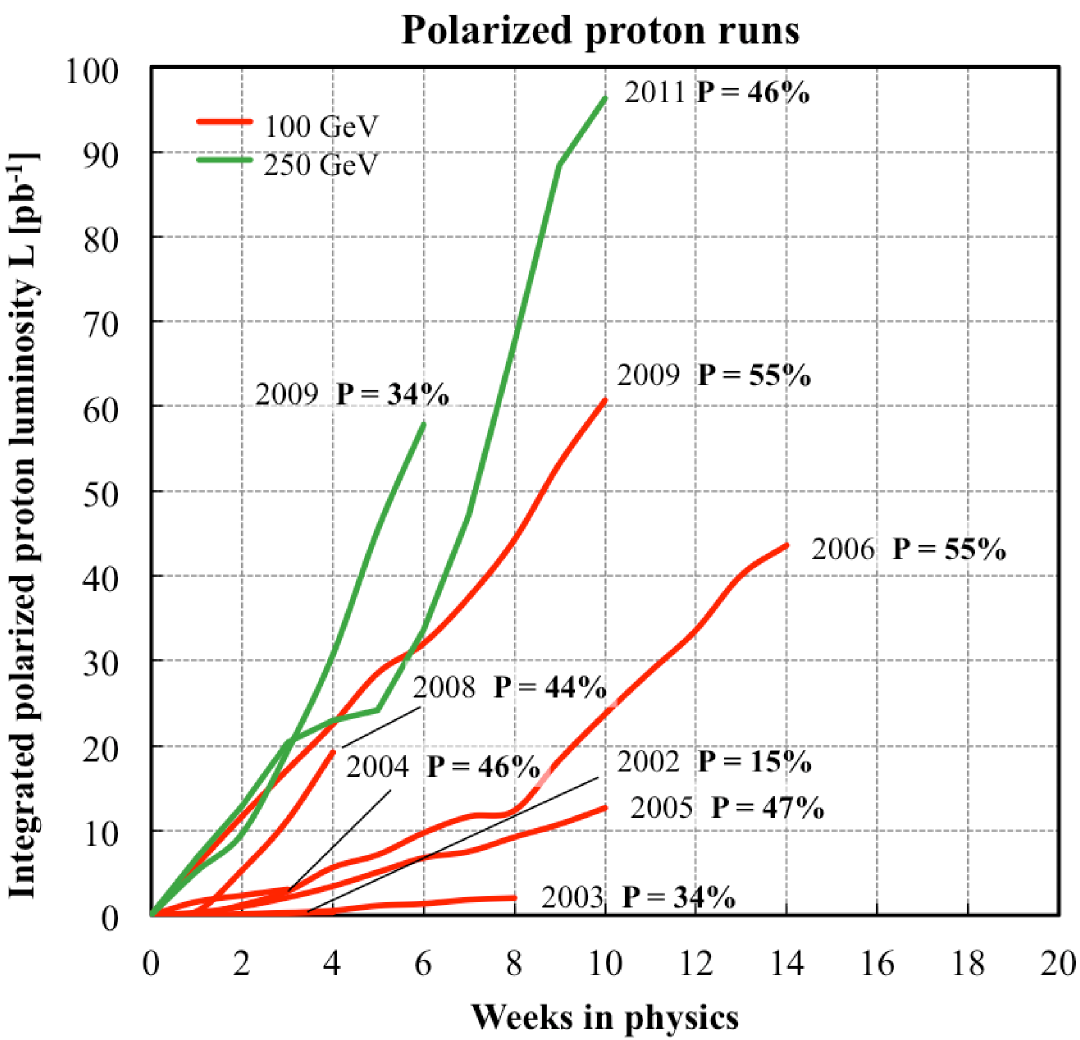


Expect smaller performance increases after Run-14

(operate close to burn-off limit, further L increase only with more beam filled or faster burn)

[Note1 :assume 12 weeks of physics, 8 weeks of ramp-up, start at ¼ of max]
[Note 2: last projections from 11 May 2010 still valid – reached peak performance goals for both polarized protons and heavy ions, will update after Run-11]

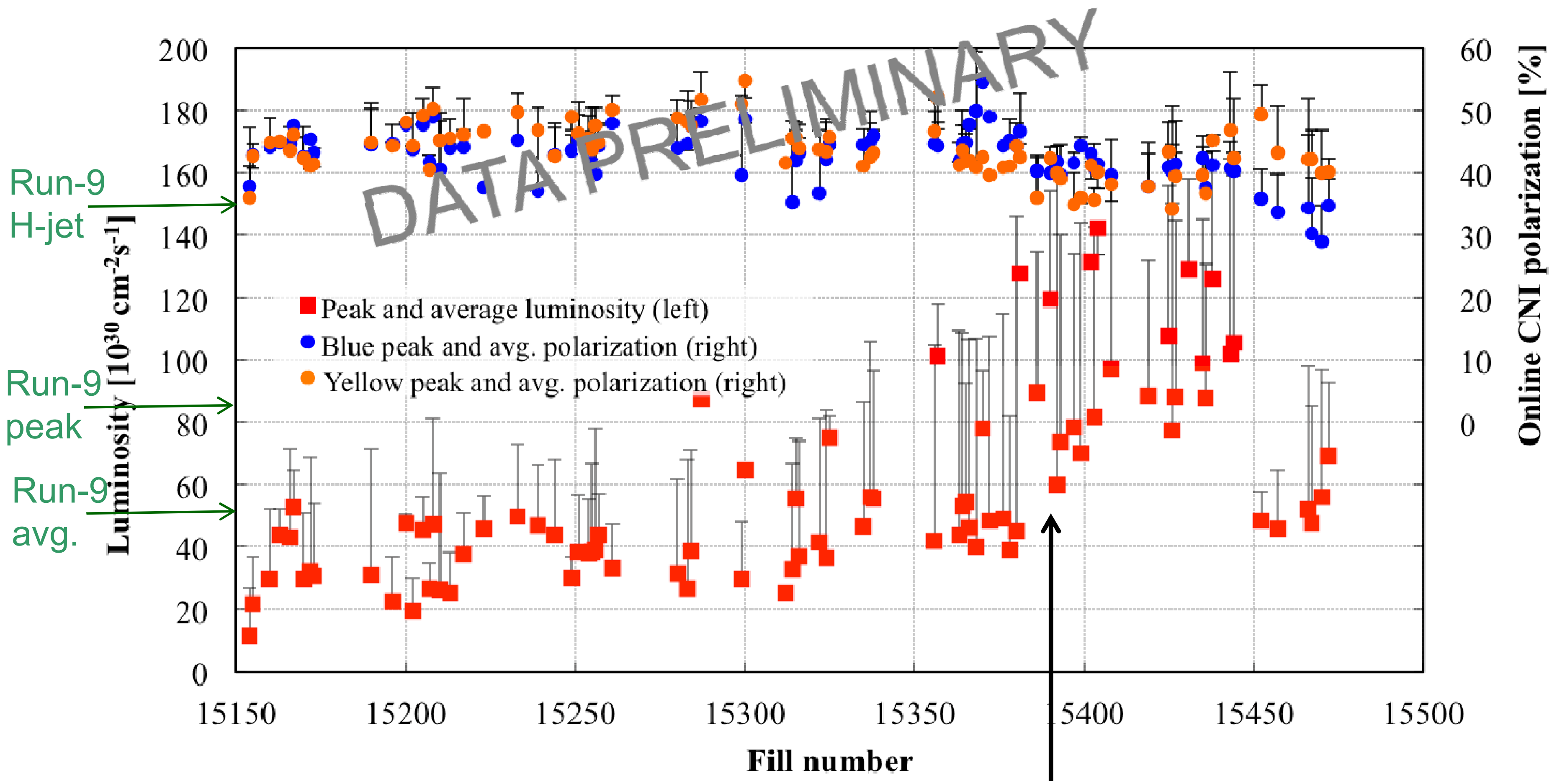
RHIC polarized protons – luminosity and polarization



- <P> increased from 37% to 46% at 250 GeV in Run-11
  still significant effort needed
  to reach goal of 70%
- Building blocks for pp design luminosity at 250 GeV demonstrated in Run-9 and Run-11
  need to be put together
  plans to go beyond
- Expect no large increase in luminosity at 100 GeV before electron lenses

Run-11 250 GeV store overview – polarization and luminosity

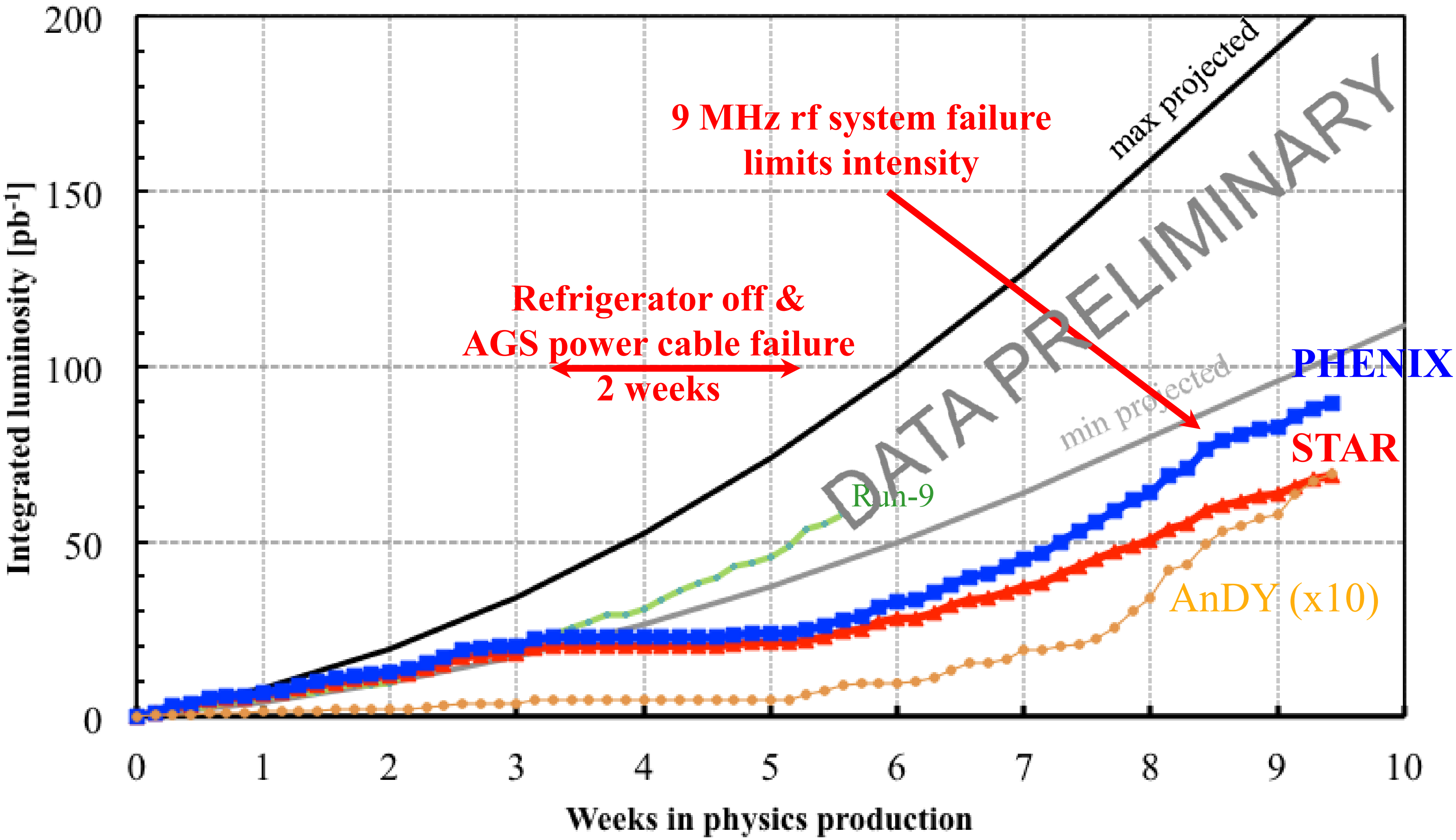
Run Coordinator: Haixin Huang



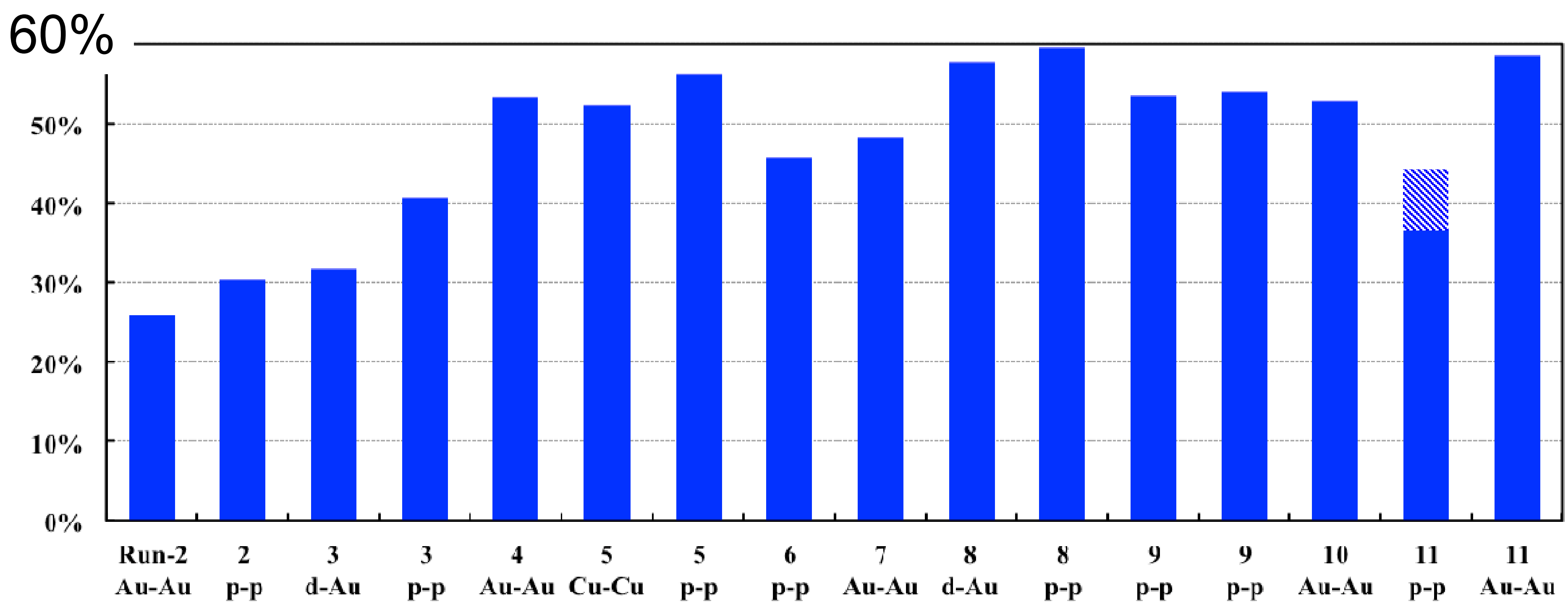
start to take full advantage
of AGS tune jump system,
feedbacks, 9 MHz rf

Run-11 polarized proton luminosity √s = 500 GeV

Run Coordinator: Haixin Huang



RHIC time-in-store history (% of calendar time)



Time-in-store in Run-11 pp lower than in previous runs

- No common reason identified for reduced time-in-store
- Increase in MTTR (Mean Time To Repair), PS overall about the same as Run-9
- 2 largest events (refrigerator off, AGS power cable) account for 9%
- Effect on performance stronger than linear (scheduling difficult, less time for implementation of improvements, more time re-establishing machine)

Unusual events in 250 GeV polarized proton Run-11

- Total of 6 snow days during start-up (>20 h excused time in January), delayed physics by about ½ week
- Fast emittance growth in Blue ring (intermittently observed in 2007 and 2009, tracked down to loose wire in dump kicker thyratron module B), delayed physics by about ½ week
- Breaker trip on 03/07/11 leads to refrigerator shut-off and helium venting in 2:00 and 6:00 service buildings, loss of about 3.5 tons of He, after repair encounter difficulties in purchasing replacement He, operation re-established on 03/17/11 – 219h downtime
- Power cable failure shut-down most of AGS equipment and part of building 911 – 78h downtime
- New 9 MHz RF system breaks 1 week before run end (current shield for bellows failing leading to overheating), luminosity cut in half

Run 11 Polarization Performance

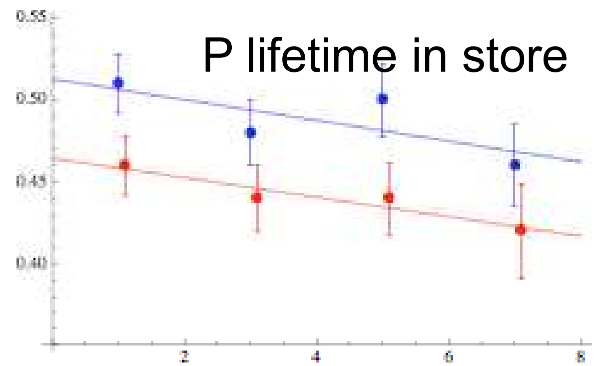
- AGS horizontal tune jump system operational: *P* +8% with high intensity
- Acceleration near Q_v = ⅔ in RHIC, measured orbit rms ~20 μm: *P* +25%
- Polarization at end of 250 GeV ramp: 53%
- With incremental improvements <P> = 55 – 60% possible for next run:

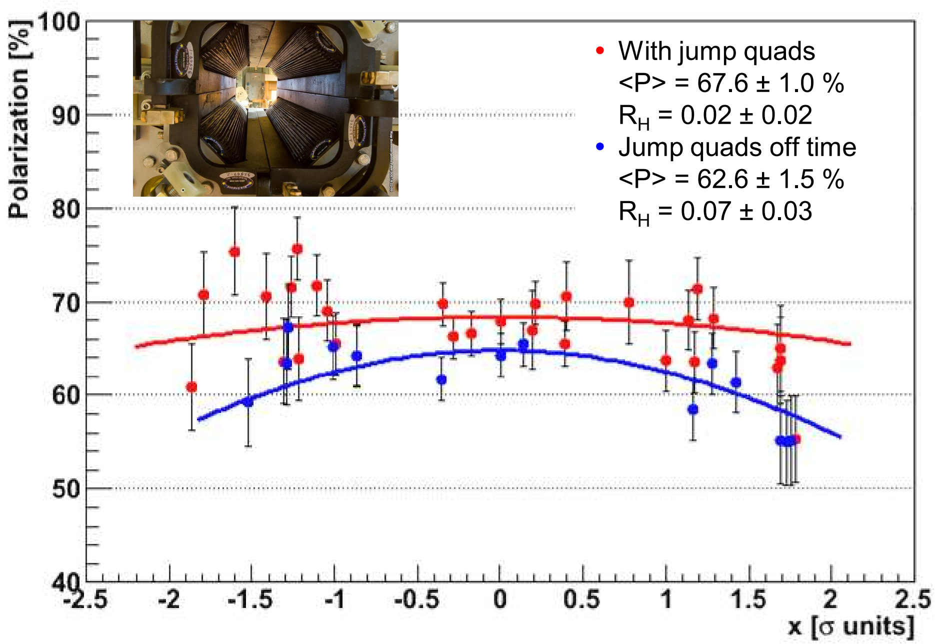
  Changes in source/LEBT/MEBT: +6% in <P>

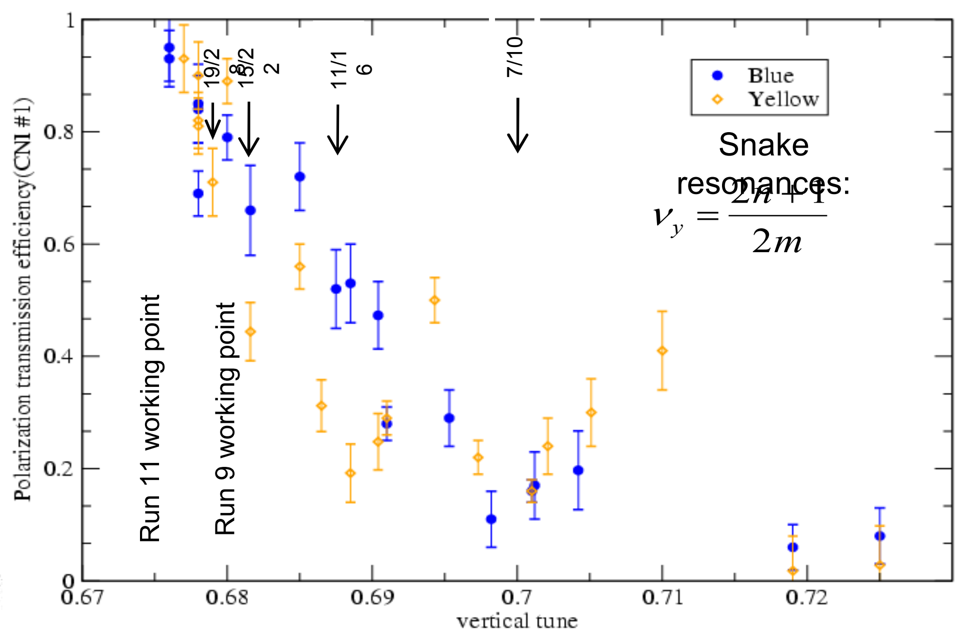
  Smaller emittance growth (24 → 18 μm): +8% in <P>

  Small change in store energy: no P decay during store: +5% in <P>

- Remaining pol. Loss during AGS (~15%) and RHIC (~15%) accel., to be studied with tracking simulations







Polarization evolution in AGS and RHIC

- Polarization loss from intrinsic resonances: polarization lost at edge of beam → polarization profile
- Impact of polarization profile on beam polarization at collisions:

$$P(x,x',y,y') = P_0 e^{-\frac{x^2+x'^2}{2\sigma_{x,P}^2}} e^{-\frac{y^2+y'^2}{2\sigma_{y,P}^2}}; \quad I(x,x',y,y') = I_0 e^{-\frac{x^2+x'^2}{2\sigma_{x,I}^2}} e^{-\frac{y^2+y'^2}{2\sigma_{y,I}^2}}; \quad R_x = \frac{\sigma_{x,I}^2}{\sigma_{x,P}^2}; \quad R_y = \frac{\sigma_{y,I}^2}{\sigma_{y,P}^2}$$

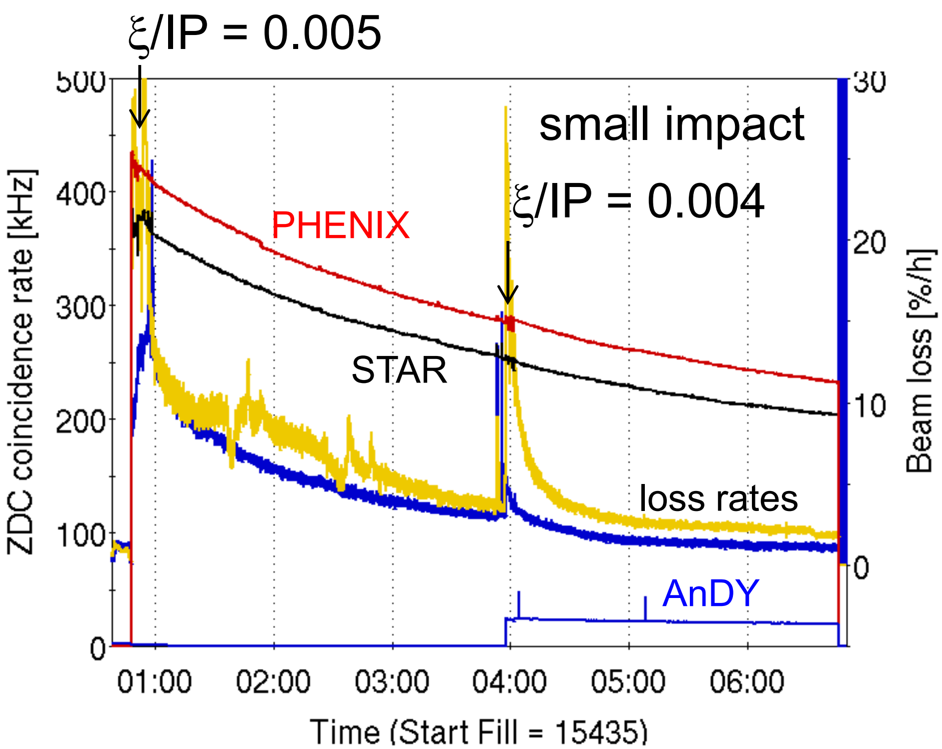
$$\langle P \rangle = P_0 \frac{1}{(1+R_x)(1+R_y)}; \quad P_{coll.} = P_0 \frac{1}{\sqrt{1+\frac{1}{2}R_x}\sqrt{1+R_x}\sqrt{1+\frac{1}{2}R_y}\sqrt{1+R_y}} = \langle P \rangle \frac{\sqrt{1+R_x}\sqrt{1+R_y}}{\sqrt{1+\frac{1}{2}R_x}\sqrt{1+\frac{1}{2}R_y}}$$

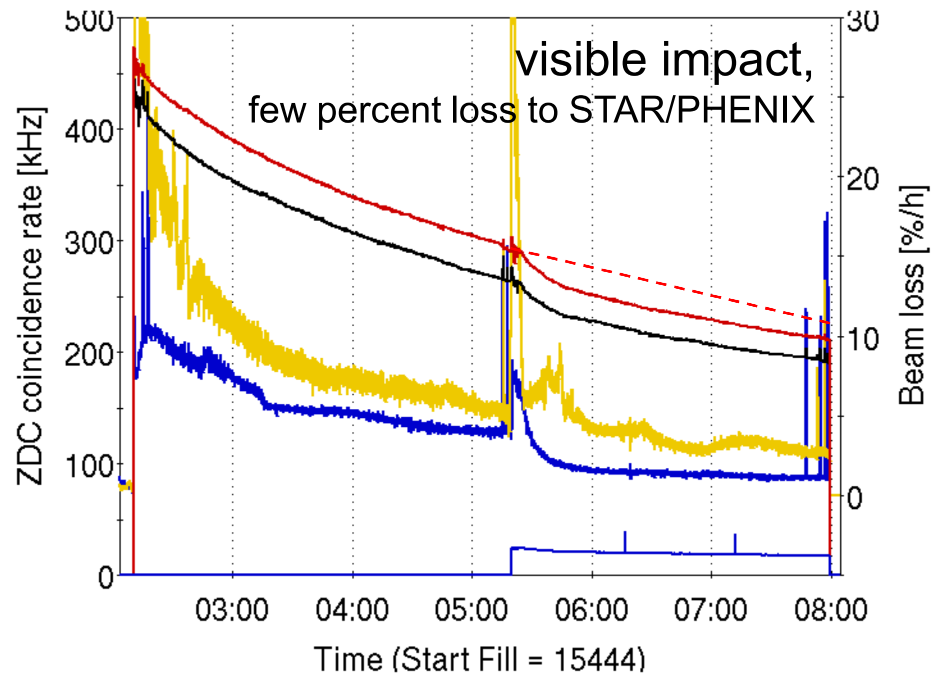
- For $R_x \approx R_y$ and small: $P_0 = \langle P \rangle (1+\langle R \rangle)^2$; $P_{coll.} = \langle P \rangle (1+½\langle R \rangle)$
- Note that P_0, the polarization of the core particle, should be equal to the maximum achievable polarization.

	<P>	**<R>**	**$P_{coll.}$**	**P_0**	**$P_{max.}$**
AGS extr.	67.6 ± 1.0	0.02 ± 0.02		70.3 ± 1.0	80.0
RHIC inj. B	65.7 ± 0.3	0.08 ± 0.02		76.6 ± 0.4	76.6
RHIC inj. Y	66.3 ± 0.3	0.08 ± 0.02		77.3 ± 0.4	79.3
RHIC 250 GeV B	52.2 ± 0.3	0.17 ± 0.02	56.6 ± 0.3	71.5 ± 0.4	76.6
RHIC 250 GeV Y	54.5 ± 0.3	0.16 ± 0.02	58.9 ± 0.3	73.3 ± 0.4	79.3

A_nDY in Run-11 (250 GeV pp)

- Beam envelope function β^* = 3.0 m at IP2
- Reduced IP2 crossing angle from initially 2.0 mrad to zero
- Added 3rd collision with following criteria (last instruction):
  1. $N_b \leq 1.5 \times 10^{11}$
  2. Beam loss rate <15%/h in both beams
  3. Not before first polarization measurement 3h into store





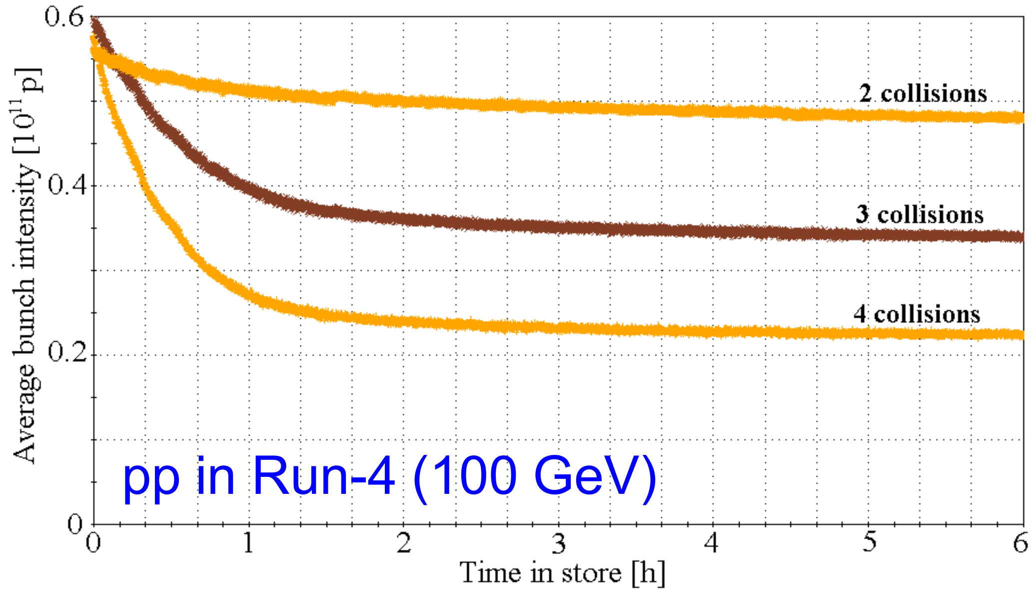
Future operation of A_nDY

- Can reduce β^* at IP2
  - have run with β^* = 2.0 m previously for BRAHMS
  - β^* = 1.5 m probably ok, needs to be tested
- Longer stores
  - 10h instead of 8h in Run-11 (depends on luminosity lifetime and store-to-store time)
- Collide earlier in store when conditions are met
  - needs coordination with polarization measurement, PHENIX and STAR
- Electron lenses (see later) if A_nDY runs beyond Run-13
  - increases max beam-beam tune spread, currently $\Delta Q_{max,bb} \approx 0.015$
  - can be used for to increase $\xi \sim N_b/\varepsilon$ and/or number of collisions

Run-11 luminosity at A_nDY:
max ~0.5 pb^{-1}/store

With improvements:
~3x increase,
~10 pb^{-1}/week (max)

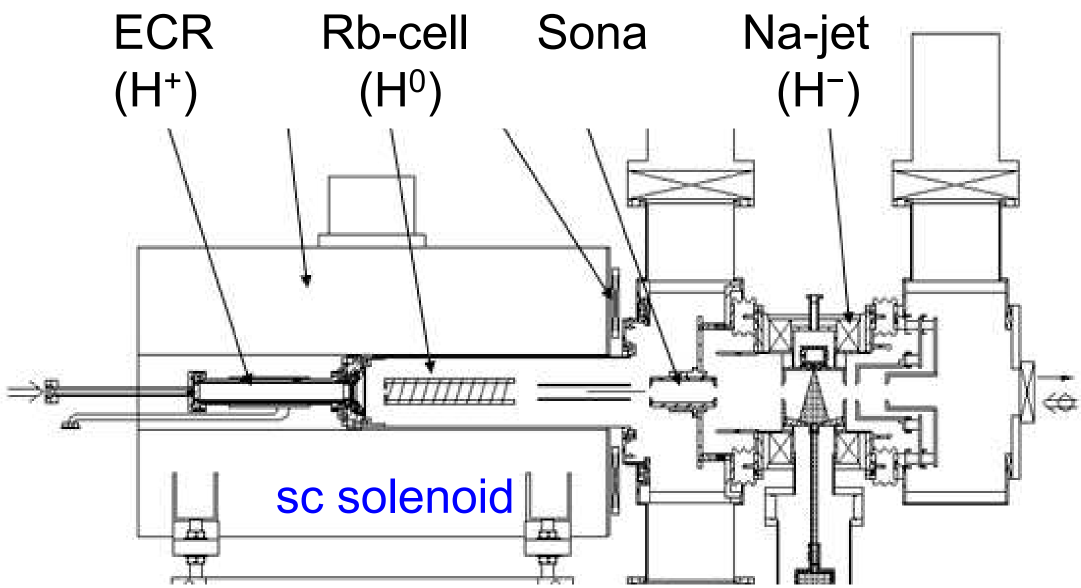
(A_nDY sees stronger impact of prematurely aborted stores than STAR and PHENIX)



Optically Pumped Polarized H^{-} source (OPPIS)

Current OPPIS

A. Zelenski, PST2009



- 29.2 GHz ECR source used for primary H^{+} generation
- source was originally developed for dc operation

RHIC OPPIS produces reliably 0.5-1.0 mA polarized H^{-} ion current.

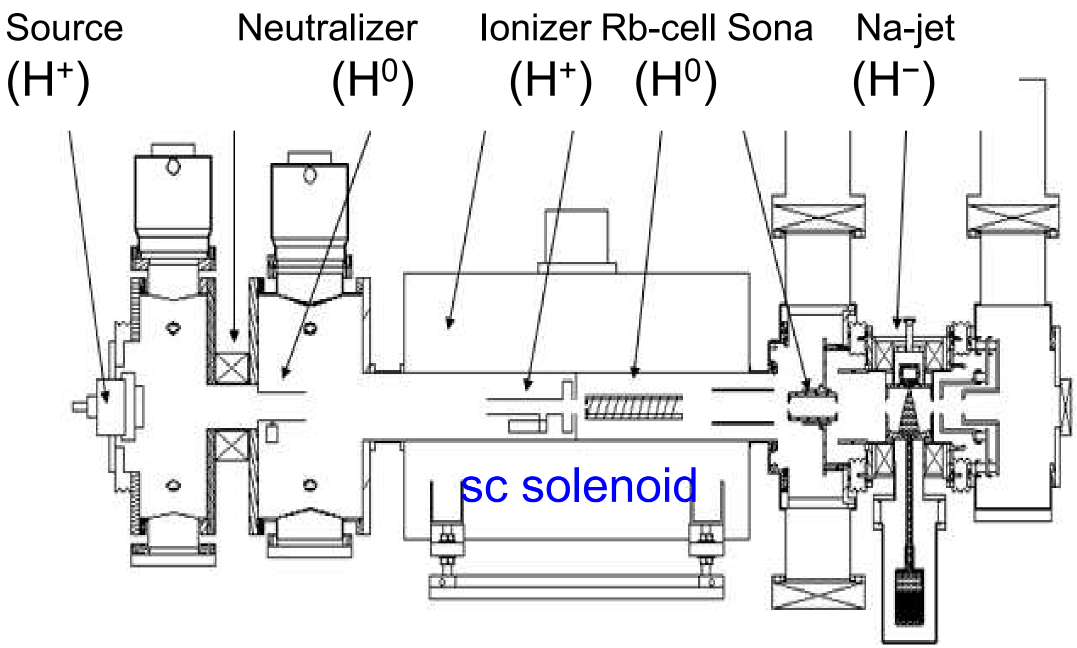
Polarization at 200 MeV:
P = 80-85%.

Beam intensity (ion/pulse) routine operation:

Source	- 10^{12} H^{-}/pulse
Linac	- 5×10^{11}
AGS	- $1.8\text{-}2.0\times10^{11}$
RHIC	- 1.8×10^{11}/bunch

Optically Pumped Polarized H^- source (OPPIS) – A. Zelenski

Upgraded OPPIS (Run-13)



10x intensity increase was demonstrated in a pulsed operation by using a very high-brightness Fast Atomic Beam Source instead of the ECR source

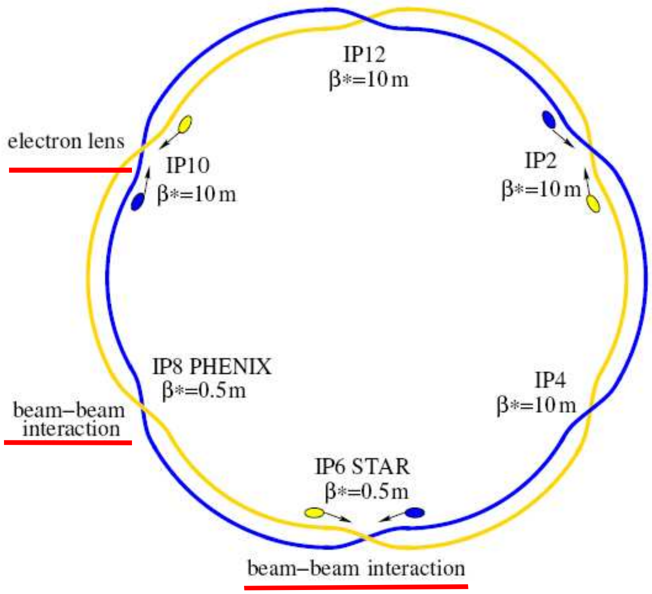
Goals:

1. H^- beam current increase to 10mA (order of magnitude)
2. Polarization to 85-90% (~5% increase)

Upgrade components:

1. Atomic hydrogen injector (collaboration with BINP Novosibirsk)
2. Superconducting solenoid (3 T)
3. Beam diagnostics and polarimetry

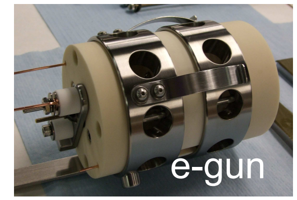
Electron lenses – partial head-on beam-beam compensation



Polarized proton luminosity limited by head-on beam-beam effect ($\Delta Q_{bb,max}$ ~ 0.02)

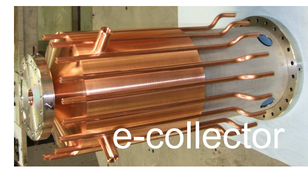
Basic idea:

In addition to 2(3) beam-beam collisions with **positively** charged beam have another collision with a **negatively** charged beam with the same amplitude dependence.

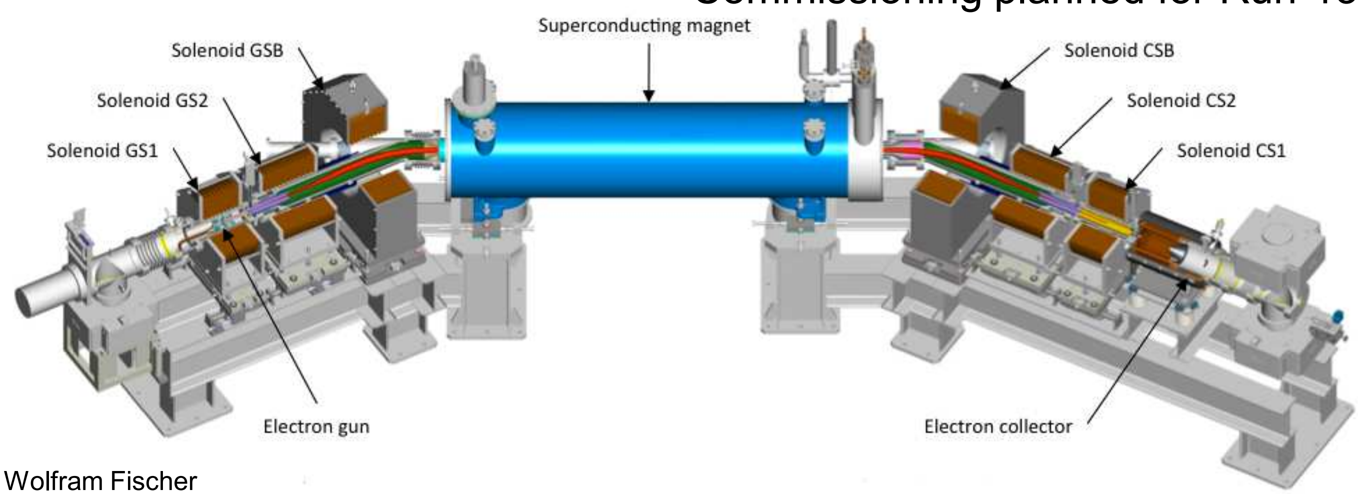


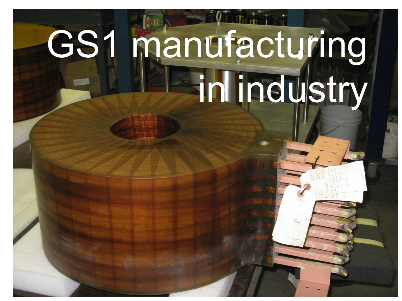
Exact compensation for:

- short bunches
- $\Delta\psi_{x,y} = k\pi$ between p-p and p-e collision
- no nonlinearities between p-p and p-e
- same amplitude dependent kick from p-p, p-e
- only approximate realization possible



Expect up to 2x more luminosity
with OPPIS upgrade
Commissioning planned for Run-13





Wolfram Fischer

Luminosity and Polarization Goals

Parameter	unit	**Achieved**	**With full stoch. cooling and 56 MHz cavity**	
Au-Au operation		**2011**	**≥ 2012**	
Energy	GeV/nucleon	100	100	
No of bunches	…	111	111	
Bunch intensity	10^9	1.3	1.1	
Average Luminosity	10^{26} cm^{-2} s^{-1}	**30**	**40**	
p↑- p↑ operation		**2011**	**≥ 2012**	**≥ 2014**
Energy	GeV	100 / 250	100 / 250	250
No of bunches	…	109	109	109
Bunch intensity	10^{11}	1.3 / 1.65	1.3 / 1.7	2.0
Average Luminosity	10^{30} cm^{-2} s^{-1}	**24 / 90**	**30 / 150**	**300**
Polarization	%	**56 / 46**	**65**	**70**

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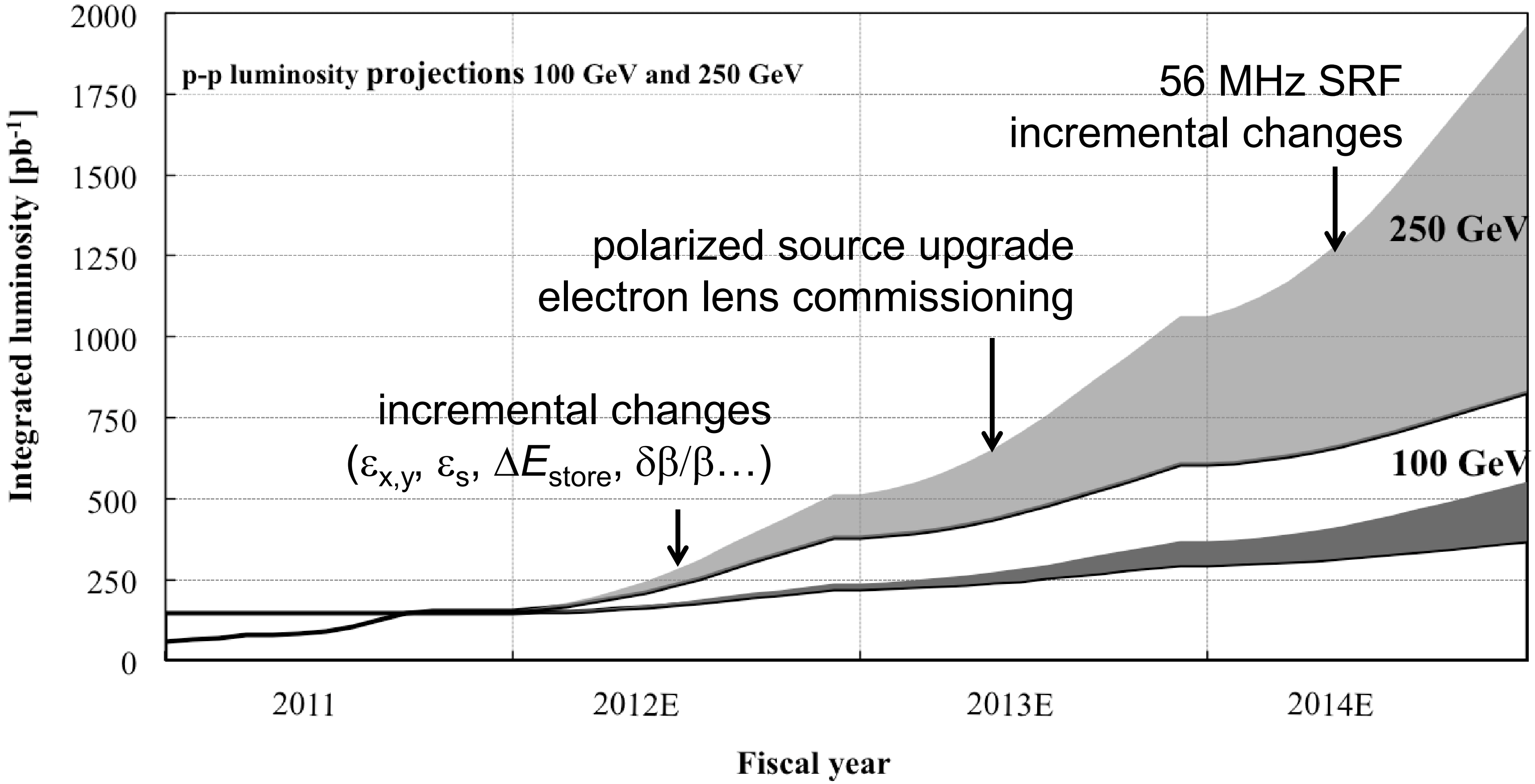
Projections for p^-p^

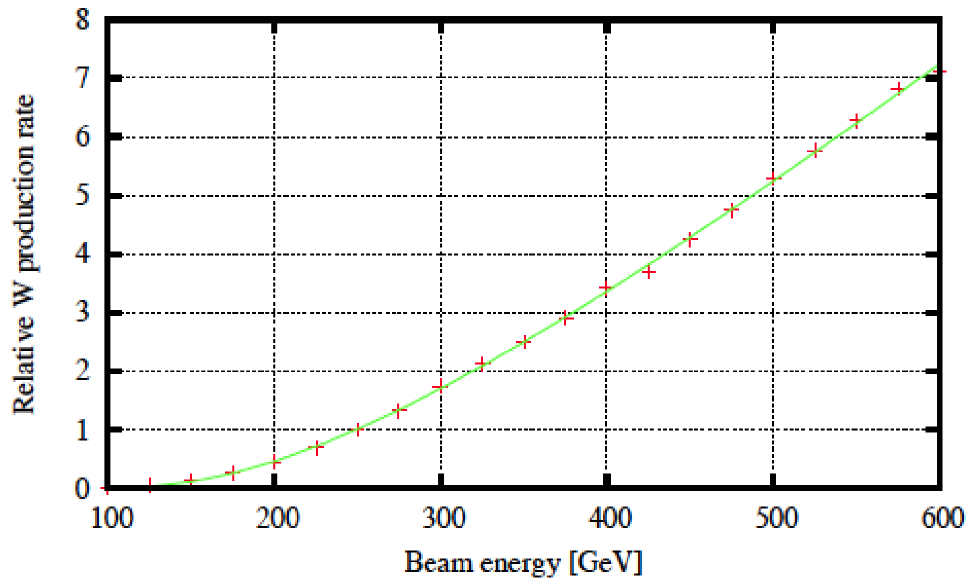


[Note1:assume 12 weeks of physics, 8 weeks of ramp-up, start at ¼ of max]
Note 2: last projections from 11 May 2010 still valid – reached peak performance goals for both polarized protons and heavy ions, will update after Run-11
Note 3: A_nDY operation with ~10 pb^{-1}/week after ramp-up

Energy upgrade – W. MacKay, BNL C-A/AP/422

Motivations:

1. Increase in W production cross section
2. eRHIC

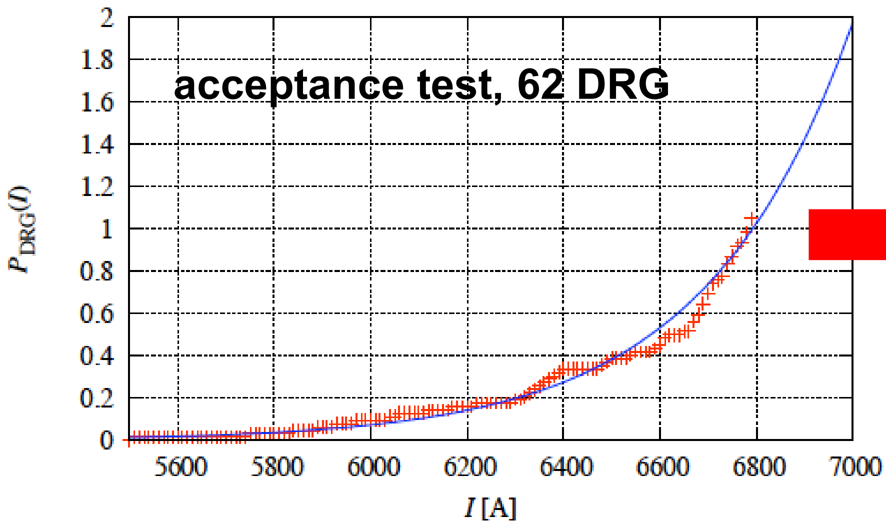


Main issues:

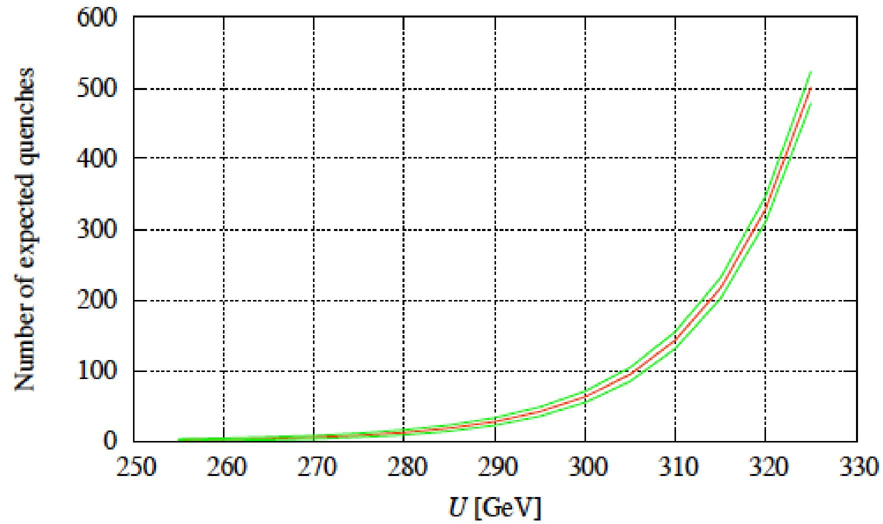
- Quench performance of magnets (DX, arc dipoles and quads, IR quads)
- Crossing angles at IPs and luminosity
- Polarization
- Current feedthroughs
- Power supplies and transformers
- Dump kicker (strength, pre-fires)
- Reliability generally reduced at higher energies

Energy upgrade – W. MacKay, C-A/AP/422

observed quenches in arc dipoles



estimated # of training quenches



Conclusion:

- 10% increase to 275 GeV (+45% in σ_W) feasible with current magnets
  about 20 DX, 10 other training quenches, more cooling at some current leads
- Requires some hardware upgrades (power supplies)
- Effect on polarization still needs study
- Energies >275 GeV require too many training quenches
  hundreds of arc dipole training quenches alone for 325 GeV

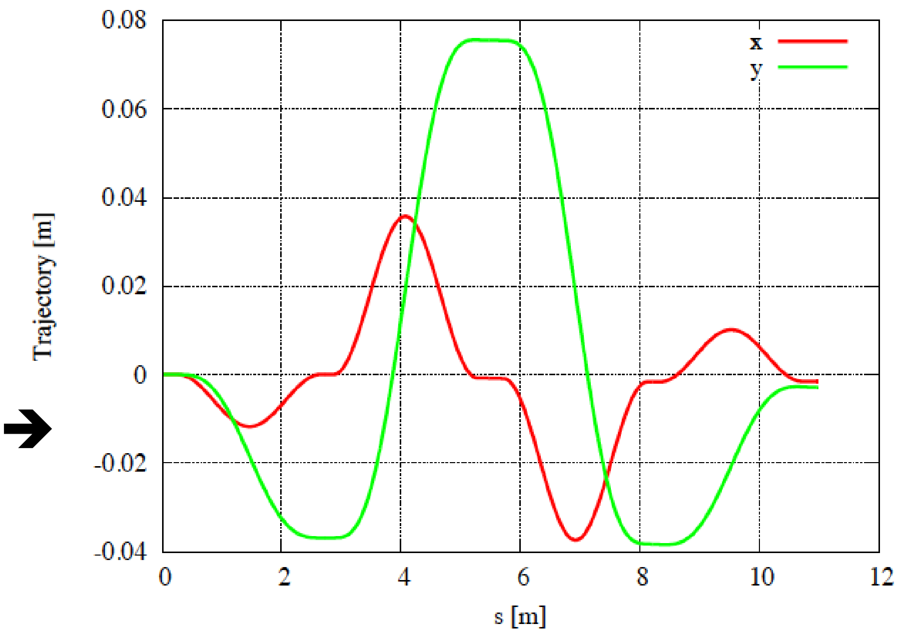
Polarized d

- Polarized neutrons for RHIC and eRHIC could be in deuterons (d = $^2H^{1+}$) or $^3He^{2+}$

	p	$^2_1H^+$	$^3_1H^+$	$^3_2He^{+2}$
M [GeV/c^2]	0.938272	1.875613	2.808921	2.808391
μ/μ_N	2.792847	0.857438	2.972962	-2.127498
$G = (g-2)/2$	1.792847	-0.142987	7.918171	-4.183963

- d very difficult at high energy (i.e. RHIC)
- Currently no technical solution for maintaining and rotating polarized deuterons ($G = -0.14$) in RHIC
- Siberian snake with B_{out} = 33.5 T, B_{in} = 101.6 T

Orbit excursion in snake for deuterons ➔



[W. MacKay, CAD MAC-05, 09/15/2010]

Polarized ^{3}He

[Summary W. MacKay, CAD MAC-05, 09/15/2010]

Deuterons not good in RHIC — perhaps in a figure-8 ring.

He^3 looks promising: no real show stoppers.

- Source: $^3He^{+2}$ OPPIS source — proposal: Milner/Zelenski
  See Anatoli Zelenski's presentation.
- $|G\gamma|_{\text{max}}$ is higher for He^3:
  - More and Stronger resonances in all rings.
- ○ ^{3}He polarimeters need to be developed.
- AGS cold snake may be sufficient at lower field.
  AGS warm snake (fixed field) might be too strong ($\sim 14\%$).
- AGS injection and extraction spin-matching: not too bad.
  - ○ Booster to AGS may need matching (depends on AGS snakes).
- RHIC snakes and rotators will work with lower fields.
- Lower injection rigidity for RHIC should be OK.
  - Injection orbit excursions reduced.

Polarized ^{3}He source R&D

- Plans to start working on ^{3}He source (MIT – R. Milner, Mainz)

- 3 possibilities discussed to use EBIS (A. Zelenski, J. Alessi et al.):
    1. $^{3}He^{\wedge}$ production outside EBIS
       limits on field gradients
    2. $^{3}He^{\wedge}$ production inside EBIS
       space and maintenance issues, P source measurement
    3. Injection of $^{3}He^{+\wedge}$ into EBIS

- In all cases EBIS ionizes to $^{3}H^{2+\wedge}$
- Aim for 2.5×10^{11} ions from EBIS, 1×10^{11}/bunch in RHIC
- Could collide ^{3}He-^{3}He or p-^{3}He at $\gamma_{max} = 178$
  (^{3}He with 166.2 GeV/nucleon, p with 167.5 GeV)

Further upgrades are possible …

Heavy ions

Once operating near the burn-off limit with short stores, only an increase in the stored beam intensity will yield more integrated luminosity

injector chain, in-situ coating and/or high-band width feedback at transition, machine protection, more longitudinal focusing on ramp, …

Polarized protons

Not burn-off dominated, reduction in beam size at IP and increase in bunch intensity up to the beam-beam limit, push out beam-beam limit

in-situ coating, machine protection, small β^* with re-build IR without DX, Coherent Electron Cooling, …

RHIC luminosity upgrade program – summary

Heavy ion upgrades

Reached: E=100 GeV/nucleon, <L>=30x10^{26}cm^{-2}s^{-1}

- Electron Beam Ion Source (U beams) – under commissioning
- Horizontal stochastic cooling (counteracting IBS, +30% L) (Run-12)
- 56 MHz SRF (counteracting IBS, +30-50% L) (Run-14)

Polarized proton upgrades (polarization, beam-beam)

Reached: E=250 GeV, <L>=90x10^{30}cm^{-2}s^{-1}, <P>=46%

- Polarized source upgrade (10x intensity, +5% P) (Run-13)
- Electron lenses (reduction of head-on beam-beam, up to 2x L) (Run-13)
- Energy increase by 10% appears feasible
- Work on polarized ^{3}He source started